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THESIS

MINESWEEPING FOR PRESSURE ACTUATED MINES BY AIR INJECTION INTO A WATER COLUMN

by

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September 2011

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13. ABSTRACT (maximum 200 words)

The U.S. Navy historically has not had an adequate means to remotely pressure-sweep for mines at reasonable speeds and cost, and this is still the case. The Navy has addressed such threats, but countermeasures are time consuming and considered to be very resource intensive. During this thesis two sets of data were collected in tow tank experiments using two different sizes of Bubble Squid apparatus. This thesis is a continuation of work already completed by Lieutenant Jeffery Murawski from December 2009. This continuation was able to extend the proof-of-concept with larger scale tow-tank testing at NPS. Further testing with the much larger three-meter Bubble Squid apparatus culminated in experiments conducted in March 2010 at the David Taylor Research Basin in Carderock, MD. The data that was collected and analyzed in this thesis will show that the Bubble Squid apparatus is a viable concept for solving the pressure influence minesweeping capability gap.

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MINESWEEPING FOR PRESSURE ACTUATED MINES BY AIR INJECTION INTO A WATER COLUMN

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The U.S. Navy historically has not had an adequate means to remotely pressure-sweep for mines at reasonable speeds and cost, and this is still the case. The Navy has addressed such threats, but countermeasures are time consuming and considered to be very resource intensive. During this thesis two sets of data were collected in tow tank experiments using two different sizes of Bubble Squid apparatus. This thesis is a continuation of work already completed by Lieutenant Jeffery Murawski from December 2009. This continuation was able to extend the proof-of-concept with larger scale tow-tank testing at NPS. Further testing with the much larger three-meter Bubble Squid apparatus culminated in experiments conducted in March 2010 at the David Taylor Research Basin in Carderock, MD. The data that was collected and analyzed in this thesis will show that the Bubble Squid apparatus is a viable concept for solving the pressure influence minesweeping capability gap.

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LIST OF ACRONYMS AND ABBREVIATIONS

BSQ	Bubble Squid
cfm	cubic foot per meter
cm	centimeter
DTMB	David Taylor Model Basin
Hz	Hertz (cycles per second)
Lbs	Pounds
lpm	liters per minute
MCM	Mine Countermeasures
m	meter
m/s	meters per second
NPS	Naval Postgraduate School
NPT	National Pipe Threads
ONR	Office of Naval Research
POC	Point of Contact
PSI	Pounds per Square Inch
PVC	Polyvinyl Chloride
RHIB	Rigid Hull Inflatable Boat
TA	Templeman Automation
USV	Unmanned Surface Vehicle

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I. INTRODUCTION

Since the invention of the pressure-actuated influence mine by the Germans in WWII, navies have had to cope with an unsweepable mine threat. Pressure influence mines use pressure sensors to detect a change in pressure of the water column above the mine as a ship is passing overhead. Some of these mines are also able to use magnetic field changes or ship noise to arm themselves. Once this arming is complete and the detonation criterion is met, mine detonation can occur. The threat level of pressure mines has only increased due to the advent of newer and more sophisticated technology. The U.S. Navy has a dedicated group of ships and staffs devoted to countering mines at sea. The Mine Countermeasures (MCM) division of the navy is an aging fleet of complicated and maintenance-intensive ships known as the AVENGER class MCMs. Despite the amount of minesweeping gear that is carried onboard each of these ships, they still don’t posses minesweeping gear for the clearance of pressure mines.

The continued threat of pressure-influence mines motivated the Office of Naval Research (ONR) to request support in creating a minesweeping device for towing behind a newly developed minesweeping asset. This new asset was an unmanned surface rigid hull inflatable boat (RHIB). The ONR selected the Naval Postgraduate School (NPS) and Templeman Automation Group (TA) to try and solve the long-standing capability gap for pressure influence mines. The decided method amongst the collaborators was the use of air bubble injection into the water column. This would be achieved using a “Bubble Squid” apparatus. For the purposes of this thesis the term Bubble Squid is defined as an apparatus consisting of a constructed framework with attached porous hosing and air hose inlet for the purpose of injecting air into the water column while being towed at varying depths and speeds. Initial Phase I testing was performed using a 1/100 scale Bubble Squid and was concluded by TA and NPS in 2009. Results from the data of the Phase I testing were received by ONR and subsequently resulted

in Phase II funding for larger scale model testing. The Phase II testing was planned to involve a 1/10 scale model. Figure 1 shows how the Bubble Squid concept is intended to produce the pressure drop as seen by a pressure influence mine as a ship travels overhead.

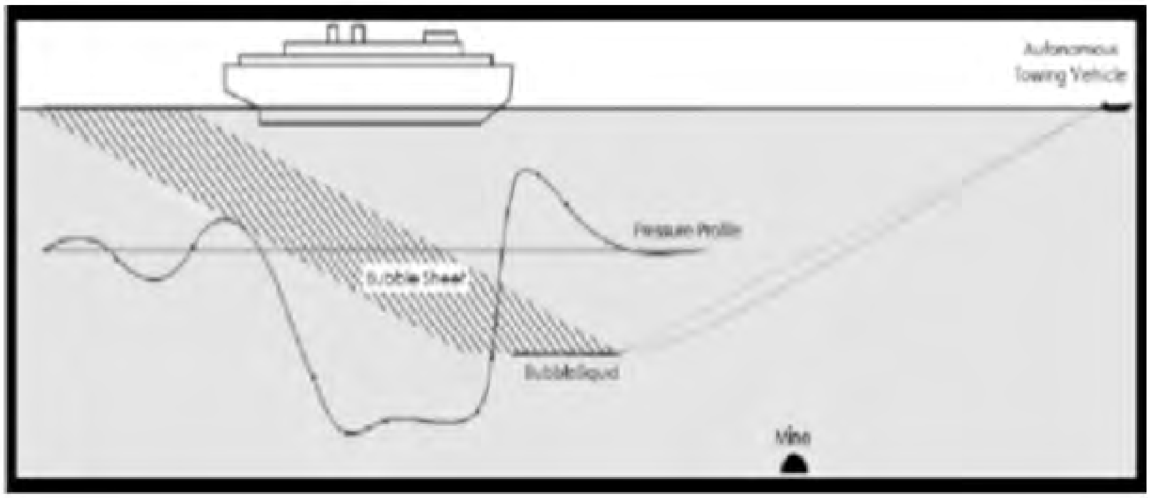

Figure 1. Bubble Squid replicating ship pressure drop

Initial design specifications provided to NPS and TA were that the final minesweeping Bubble Squid would have to provide a 30 meter sweep width. The initial Phase I testing was represented by a 1/100 scale, 0.3 meter, Bubble Squid model. Once approval was given to move into Phase II testing, a larger 3 meter Bubble Squid was constructed. The whole purpose behind developing the Bubble Squid concept was to inject enough air into the water column while the squid was towed at depth and speed (Figure 2). Bubbles injected into the water column would lower the density of that area which would in turn reduce the overall weight. This reduction of density and weight causes a drop in pressure that is measured by a pressure sensor. The goal of the Bubble Squid is to produce the same effect as the change seen by pressure sensors when large vessels pass overhead.

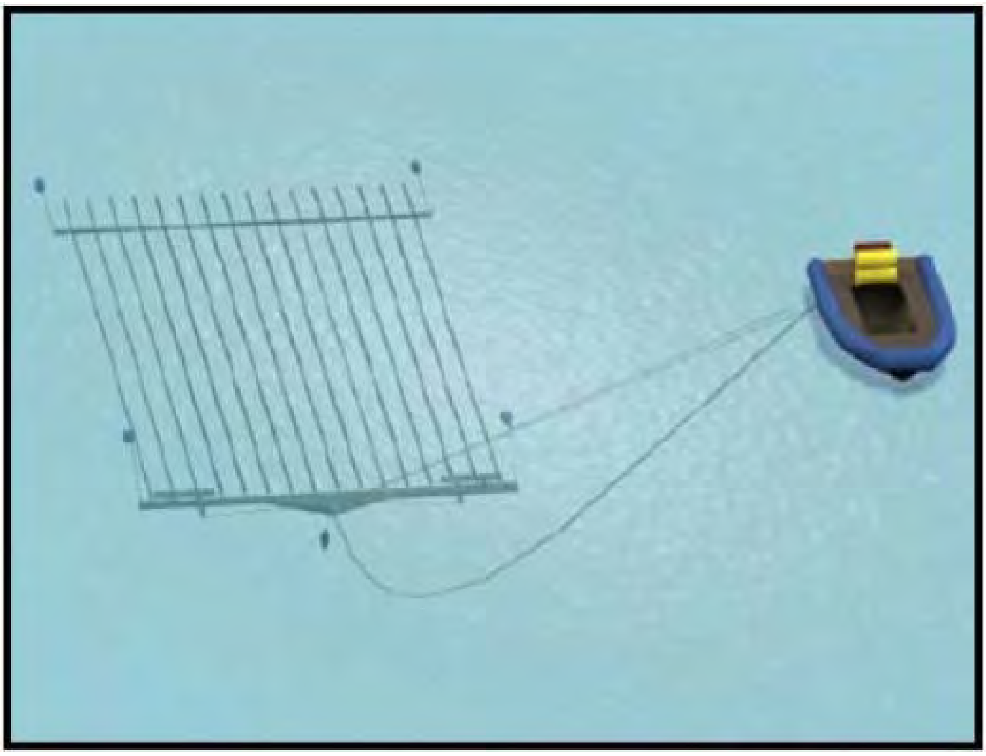

Figure 2. The Bubble Squid concept

Throughout this thesis the use of the terms “we” and “our” refer to the NPS/TA collaboration team. Based on the simple theory described above, the goal was to design and build the best possible model Bubble Squid to test the theory with experimentation in water. Initial Phase I testing was performed using both a flow tunnel and tow tank experiments at NPS. Figure 3 shows both the tow tank and flow tunnel used at NPS for initial Phase I testing.

Phase I re-verification of theory was conducted on the Naval Postgraduate campus in Spanagel Hall by TA and NPS. Phase II testing required U.S. Navy support at the David Taylor Model Basin in Carderock, Maryland, as well as TA and NPS.

Previous attempts had been made using bubbles to solve the pressure mine problem; however, none had been successful thus far. Previous experiments did not meet one of the two required ONR prerequisites of a 1 - inch pressure drop with a ten second duration. Examples of using bubbles for

minesweeping were found as far back as 1953. This oldest example was from a study performed by Yale University for the U.S. Government. Their findings were summarized as follows: “Extension to full-scale is believed to be feasible, but no engineering estimate of cost of such full-scale test has been attempted. It is clearly beyond the range of the Yale Contract as now limited and recommendation as to further work will be made to ONR later” (McKeehan, 1953). Other attempts have been made over the years to use bubbles for minesweeping, but none have been successful to the scale required by our team.

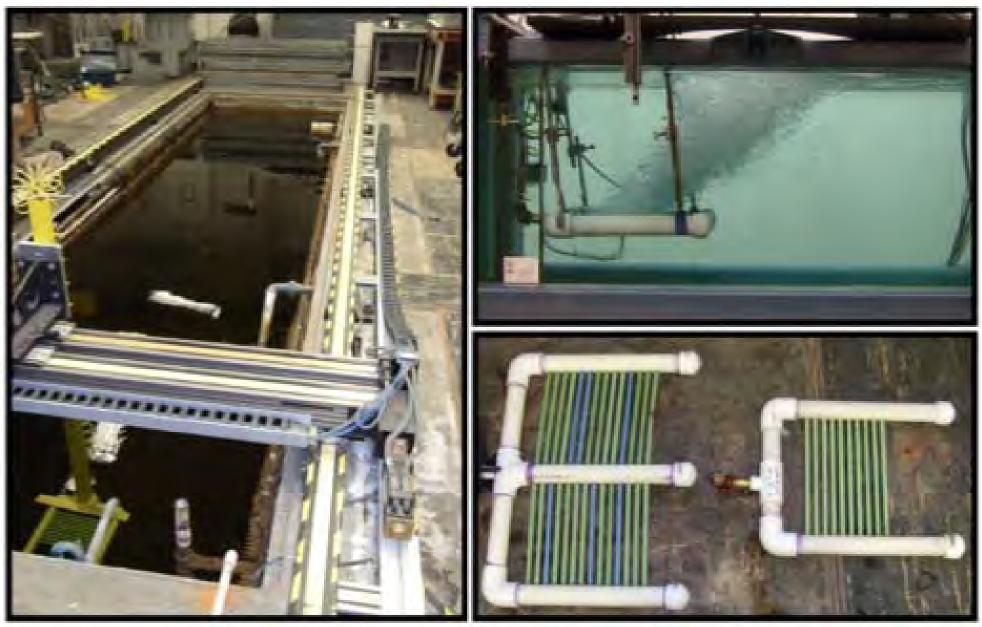

Figure 3. NPS tow tank (left), flow tank (top-right) and two of the Phase I Bubble Squids (bottom-right)

This thesis starts with an explanation of the theory behind the pressure drop resulting from air introduction into the water column in Chapter II. Next, the equipment used for laboratory testing in the tow tanks is in Chapter III. Chapter IV covers the details of the NPS tow tank facility, testing procedures and results from testing completed in March 2010. Chapter V covers the details of the David Taylor Model Basin tow tank facility, testing procedures and results from testing

completed in May 2010. Finally, there will be a synopsis of what was discovered during testing and consideration of future work that can and should be completed for solving the pressure minesweeping capability gap.

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II. THEORY

Experiments have been performed that show that a pressure drop occurs underneath a bubble field injected into the water column. It is important to be able to predict the details of this pressure drop expected for a broad range of conditions. This theoretical prediction would also provide a basis for understanding whether or not the pressure drop is a static effect or if in fact the induced flow within the water column affects the observed pressure drop. In this chapter, we develop a theory for the magnitude and duration of this static pressure drop.

We assume an ideal geometry (Figure 4) in which the bubbles rise vertically from the towed Bubble Squid. That is, the bubbles do not diffuse horizontally; the horizontal cross sectional area of the bubble field is uniform with the value wL, where w is the width and L is the length of the bubble field. We also neglect dynamic effects that occur due to the bubbles, i.e. any motion of the water due to changes in the pressure or from being entrained in the rising bubbles. The hydrostatic pressure drop can be calculated from the volume of the bubbles injected into the water if the bubbles rise sufficiently slowly, and if the sensor is located sufficiently near the bubble field.

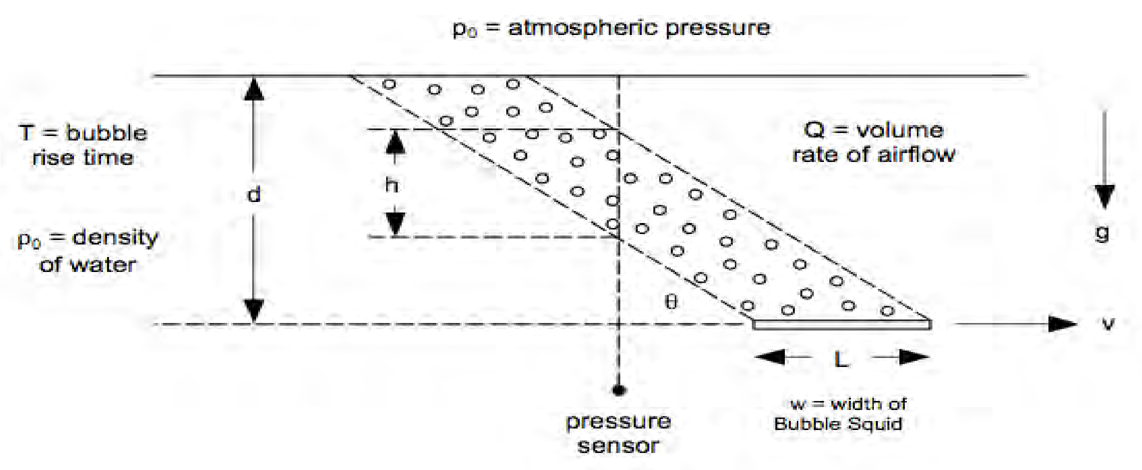

Figure 4. Geometry and parameters of an ideal bubble field from a towed Bubble Squid

We let p be the pressure of air going into our Bubble Squid, and Q be the air flow rate. For bubbles to enter the water column out of the porous hoses of the Bubble Squid, the pressure p must be larger than atmospheric pressure p_0 combined with minimum of the pressure head seen at the Bubble Squid. The pressure head is $\rho_0 gd$. If pressure were to not exceed the pressure head margin then no air flow from the Bubble Squid would exist. We make the assumption that p equals $p_0 + \rho_0 gd$. This means that we are going to neglect any value of a p that is greater than $p_0 + \rho_0 gd$, which could be compensated by surface tension provided by the bubbles. Because of the assumption of pressure remaining constant, then any measured volumetric flow rate Q would be equal to the flow rate entering the water through the Bubble Squid. Other assumptions made are as follows: that bubbles will not be expanding as they rise to the surface and that rise time is independent of the velocity v of the Bubble Squid being towed through the water. Because the bubble could “pinch off” more quickly due to Bubble Squid velocity, rise time could increase with an increasing velocity. However, this possible effect is also neglected.

With the above assumptions made, the void fraction f can be calculated for the bubble field that will be produced. The void fraction is the ratio of the volume of air put into the water divided by the total volume wLd of the bubble field. The towed Bubble Squid causes a horizontal shearing effect on the bubble field produced, thus the volume remains constant. This means that the total volume of air that can be found in the water at any time is the product of the air flow rate Q and bubble rise time T, where the rise time corresponds to the vertical distance d from the Bubble Squid to the water surface. The void fraction is thus calculated by

$$f = \frac{QT}{wLd}. \tag{2.1}$$

The void fraction is important, because it allows us to calculate the pressure drop due to the bubbles. In the water without bubbles, the pressure head due to the column of height h (refer to Figure 4) is $\rho_0 gh$. The pressure head due to the bubble field is $(1 - f)\rho_0 gh$, where we neglect the density of air compared to the density of water without bubbles, which is a very good approximation. The pressure drop due to the bubbles in the water is calculated by

$$\Delta p = f\rho_0 gh \ . \tag{2.2}$$

It should be noted that the result correctly reduces in the two limiting cases to f = 0 (no bubbles) and f = 1 (no water in the bubble field).

We can then determine the height h in Figure 4 as follows. Consider the right triangle formed by h and L. This triangle is similar to the right triangle formed by the velocity v of the Bubble Squid and the velocity s = d/T of a bubble. The similarity implies that h/L = s/v, or

$$h = \frac{Ls}{v} = \frac{Ld}{vT} \ . \tag{2.3}$$

Substituting this result into Eq. (2.2) yields

$$\Delta p = \frac{f\rho_0 gLs}{v} = \frac{f\rho_0 gLd}{vT} = \frac{Q\rho_0 g}{vw}, \tag{2.4}$$

where we have substituted the void fraction (2.1) to obtain the third expression. It is more physical to express a pressure drop in terms of effective height Δz of water. That is, we set $\Delta p = \rho_0 g\Delta z$ in Equation (2.4). The result is

$$\boxed{\Delta z = \frac{fLs}{v} = \frac{fLd}{vT} = \frac{Q}{vw}}\ . \tag{2.5}$$

We also require the persistence time τ, which is defined to be the time during which the full pressure drop Eq. (2.5) occurs. If the bubble rise time is less than the time required for the sled to move over the sensor, the full pressure drop never occurs. Bubbles start to reach the surface before the sled has passed over. However, assuming that the sled is deep enough and short enough such that the rise time is longer than the sled passage, the persistence time is given by:

$$\boxed{\tau = T - \frac{L}{v}}. \tag{2.6}$$

In other words, the persistence time is equal to the bubble rise time minus the time required for the sled to pass over and deposit the maximum volume of air directly above the sensor..

The following data were taken in the NPS tow tank during the week of 8 March 2010:

Bubble Squid dimensions:	$L = 120$ cm	$w = 40$ cm
Tow sled velocity:	$v = 0.33$ m/s	
Bubble rise time:	$T = 5.25$ s (average value)	
Airflow rate:	$Q = 270$ ℓ/min	
Bubble Squid depth:	$d = 180$ cm	
Measured pressure drop:	$\Delta z_{exp} = 0.08$ in	
Duration:	$\tau_{exp} = 5.5$ s	

The bubbles appeared to rise slowly. Substantial lateral spreading was observed, both along the towed direction and perpendicular to it.

The flow rate is $$Q = 270\frac{\ell}{\text{min}} \times \frac{(10\text{ cm})^3}{\ell} \times \frac{1\text{ min}}{60\text{ s}} = 4500\frac{\text{cm}^3}{\text{s}}.$$

From Eq. (2.1), the void fraction is calculated to be

$$f = \frac{QT}{wLd} = \frac{4500\frac{\text{cm}^3}{\text{s}} \times 5.25\text{ s}}{40\text{ cm} \times 120\text{ cm} \times 180\text{ cm}} = 2.7\%.$$

The bubble velocity is $$s = \frac{d}{T} = \frac{1.80\text{ m}}{5.25\text{ s}} = 0.34\ \frac{\text{m}}{\text{s}}.$$

.

The predicted hydrostatic pressure (2.5), measured in height of water, is

$$\Delta z = \frac{Q}{vw} = \frac{4500\frac{\text{cm}^3}{\text{s}}}{33\text{ cm/s} \times 40\text{ cm}} = 3.4\text{ cm} \times \frac{1\text{ in}}{2.54\text{ cm}} = 1.3\text{ in}.$$

This predicted value is approximately a factor of 17 greater than the observed value of 0.08 in. So our performance was initially much lower than what we had calculated. For lateral bubble diffusion to account for this large error, there would have to be a spread by roughly a factor of 4 in each of the two directions, which appears to be much more than what was observed. From Eq. (2.6), the calculated persistence time is τ = 5.25 – 1.2/.33 = 1.6 s, which does not agree with experimental persistence time, τ_{exp} = 5.5 s. It is assumed that these errors are due to the fact that our presented theory does not take into account any dynamic effects.

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III. EXPERIMENTAL APPARATUS

A. PRESSURE SENSING EQUIPMENT

1. The Sensing Challenge

During Phase 1 (1/100 scale model), one of the most time-intensive components of data capture was figuring out how to calibrate our system to detect signals on the same scale as the system noise. Even with well-designed, low noise electronics, capturing the small pressure changes induced by our scaled down bubble array was a challenge. Typical outputs for a 0-15 psi sensor are 0–5 V or 0–10 V, so when attempting to capture 1/10 inch resolution we require a system resolution of about 2 mV for the 0-10 v sensor since one inch H_2O is equal to 0.036 psi. Figure 5 shows the experimental noise floor determination.

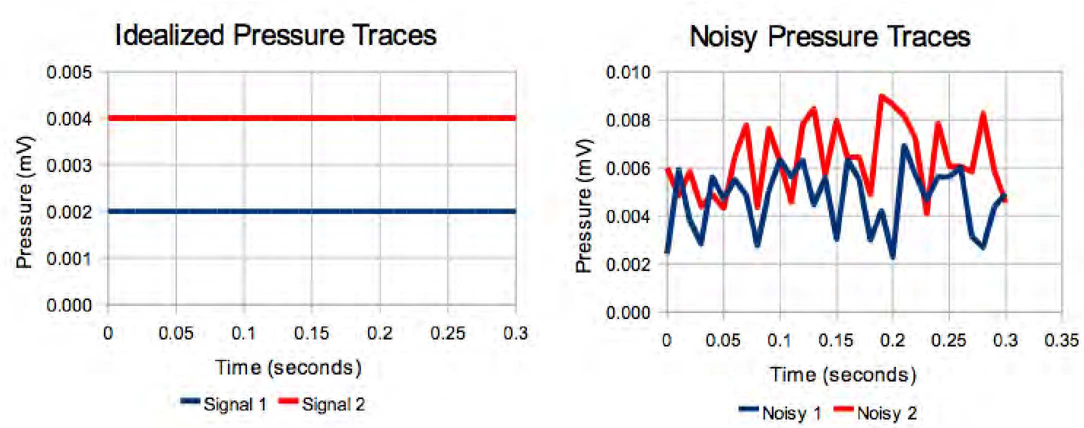

Figure 5. Standard Deviation of Noisy Pressure Signal

It is possible to pull these signals apart statistically in a static example like this, but it becomes much more complicated when the signal varies with time.

As the Bubble Squid program advanced, it became apparent that the testing facility required for performing these experiments was going to be even larger, more accurate, and more expensive. This made it imperative that our group transition to a more efficient sensor system that would allow for faster

feedback. It should be noted that the new pressure sensor chosen had a dramatic improvement for the signal to noise ratio.

2. Laboratory Pressure Sensing

Since the inception of the Phase I program, pressure sensing and data acquisition equipment was procured in order to establish new measurement capabilities for our collaboration team from Templeman Automation and NPS. The original equipment is shown in Figure 6.

Figure 6. Manometer (left) and pressure sensor (right)

Initial data was taken using a digital manometer in a tank at the Templeman Automation home office. Results from this testing showed a definitive 0.1 inch pressure drop for a 6-inch bubble column. This result was exciting, because it verified the data that was presented in the proposal to ONR for solving our problem. It gave us confidence that we could meet the specifications desired for the Bubble Squid apparatus, which again was at least a 1 inch H_2O pressure drop for a ten second duration.

3. Fieldable Pressure Sensor Design

Unlike the single pressure sensor used during Phase I testing, a new sensor design was implemented for Phase II testing at David Taylor Model Basin using an array of eight pressure sensors based. Both stock and custom Omega sensors were used. The part number of the customized Omega sensor was designated by Omega as MMA030V5P2L2T3A5, and the stock version used was MMA030V5P2C0T3A5CE. The difference in these two parts was only in the different cable receptacle used. These sensors were mounted inside a watertight can with gland-type seals on the front and back lids. Waterproof cable connectors were used on the lid. The part number for the cable connector mounted to the can was Teledyne Impulse LPMBH-4-FS and the part number for the cable with connector was Teledyne Impulse LPMIL-4-MP on 75ft of Belden 8424 cable. The Omega Company provided the housing design plans. The housing units had to be built for each one of the pressure sensors to be used in the experiments performed at NPS and DTMB.

B. DATA COLLECTION SYSTEM AND CALIBRATION

Based on pressure sensor performance, a data acquisition system was developed that would balance digitization speed, channels available, and precision to arrive at the required measurements for both sets of tow tank testing. Based on the NPS pressure signature data and the requirements of the program, resolution of a pressure change of ±0.1 inches of water head at a time resolution of 0.1 seconds was determined to be the system goal. The data acquisition board used for evaluation was a National Instruments NI USB-6210.

1. Acquisition System Benchmarking

The goal was to establish the averaging and sampling rate needed to achieve the desired precision and time resolution. Data acquisition and testing had been performed in a static tank at TA using the before mentioned manometer. We then started by using raw data applied to the Omega sensor

sampled at 40kHz for ten seconds while the water level was continuously increased by 0.1875 inches per second. This resulted in a data set of 300,000 voltage points after removal of extraneous data.

To establish the standard deviation of this data set, a linear fit to the pressure trend was performed and subtracted from the data. The sensitivity of the unit was 4.8 mV per inch of head. The un-averaged standard deviation was found to be 2 mV. Once the trend was removed, a histogram of the data was performed. This histogram suggested that the noise associated with the selected pressure sensor was very symmetric and displayed a Gaussian distribution. Based on a Gaussian distribution, smoothing was performed at 5, 10, 15, 25,50, and 100 points. At each smoothing setting, the standard deviation was calculated. For purely Gaussian noise, it would be expected that the standard deviation would fall off with a square-root relationship to the number of averaged points. The best fit that was calculated showed that the data matches the square root law well, but beats the expected gain for smoothing below 20 points and slightly lags the theoretical result for averaging above 20 points.

Based on the data gathered and analyzed from the static tank testing, the goal of ±0.1 inch precision would require an improvement of the standard deviation by 3.84 times for one-sigma (78% of data within error bars) or twice that for two-sigma (90% of data within error bars). A 20-point average improves the standard deviation to 0.4 mV and 100 samples gives 0.2 mV. In order to get good data, with 90% of data points falling within a ±0.1 inch error bar, about 100 point averages should be taken. To achieve this at a 0.1 second resolution (10Hz) then sampling must be taken at 1 kHz. It was decided that to give some room for error and additional averaging, 2 kHz would be a better sampling rate. The final distribution of the 100-point averaged data was as expected. Ninety percent of the data was found to be within ± 0.4 mV. This corresponds to approximately ±0.1 inch of head. As expected, the width of the data trace was nearly the same as the change in the overall signal for a 0.1 inch change in pressure.

C. BUBBLE GENERATING EQUIPMENT

1. Bubble Makers

Three original devices were considered for bubble generation. These were an aquarium sintered ceramic air stone (bottom), an aquarium porous rubber tube (middle), and a sintered rubber soaker hose sections (top), all of which are shown in Figure 7.

Figure 7. Bubble Squid bubble generating devices

As part of an initial scale-up test, a 25-foot section of 0.650-inch inner diameter soaker house was attached to an air compressor. After the compressor was turned on, a large bubble field was generated with only modest pressure (less than 20 psi). Work was later performed in Phase I to quantify the variables associated with this testing in order to provide the design parameters used for the 1/100 and 1/10 scale Bubble Squid prototypes.

2. Bubble Squid Design

Initial 1/100th scale model designs were constructed using PVC piping, metal hose quick disconnects and the selected porous hosing and small wire to help keep the hoses in place during testing. Both TA and NPS constructed Phase I Bubble Squids. Initial ideas for constructing the larger 1/10 scale model were based on the materials used in Phase I testing. The original design

consisted of a 10 ft PVC manifold (to be towed perpendicular to the direction of travel) with 21 penetrations (every 6 inches) for valves and/or quick disconnects to connect the bubble making hoses. Unfortunately both the valves and PVC manifold failed under modest pressure testing. The valves were tightened and passed modest pressure testing. However the PVC manifold itself continued to have leaking issues. The leaks in the PVC came from what looked like superficial scratches. Considering the ease with which PVC becomes compromised with small scratches, it was determined that PVC would be an unacceptable construction material for the Phase II 1/10 scale Bubble Squid.

Based on this testing, NPT valves and PVC were not used again for any testing at NPS or DTMB Bubble Squid testing. So our team was forced to redesign a 1/100 scale model using an aluminum manifold and welded connections for tubing. This redesign was one of the main reasons that additional tow tank testing at NPS was required. It was understood that data acquisition and analysis would be mandatory based on the new materials prior to construction of a 1/10 scale model that would be used at DTMB. The original concept of using valves or quick disconnects was intended to ensure rapid reconfiguration of the Bubble Squids hoses during testing. It was determined that hose clamps and capped off hoses would be sufficient. Hose clamps and capped off hoses were found to be quick to install, cost effective and much more reliable than originally anticipated. A more detailed description of each Bubble Squid used for testing in this thesis will be provided in each of the individual testing chapters.

IV. NPS TOW TANK EXPERIMENT

During the week of March 7, 2010, Templeman Automation and our NPS team conducted a second set of testing in the tow tank located in the basement of Spanagel Hall, room 025, at NPS. The goal of these experiments was to test the sensors and data acquisition system that were going to be used at Carderock and to further investigate the pressure signal dependence on depth, speed, bubbler/sensor separation, and air flow. Previous testing for Lieutenant Jeff Murawski's thesis (2009) had been performed in the same tow tank: however, it was based on the initial PVC manifold, our testing was with the aluminum manifold.

A. FACILITY SPECIFICATIONS

The tow tank dimensions are 21 feet long (X direction) and both 7 feet wide (Y Direction) and 7 feet deep (Z direction). Along the top of this tank is a computer-operated gantry system operated by a simple computer system. The operating system allows for the user to select tow speeds up to 1 meter per second with a maximum distance traveled on each run of approximately 18 feet. The system has safety cutouts, which do not allow the track system to use the entire length of the tank. These safety features are incorporated to protect the entire system as well as any gear that may be attached to the gantry. Figure 9 provides a visual image of how the rail system and attached gear are used in the tow tank facility at NPS. To be able to place the Bubble Squid in the water and adjust the depth throughout during data collection experiments, a ten-foot yellow stanchion with incrementally drilled holes is attached to a central point on the gantry of the rail system. It should also be noted that the rail system can be adjusted for data runs along the Y axis, however this feature was not used for this data collection because our concern was only on the pressure drop above the pressure sensor.

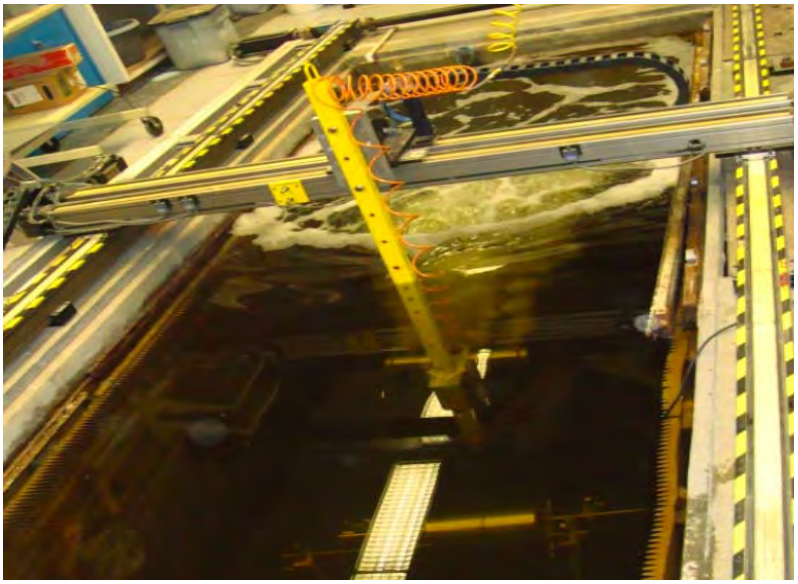

Figure 8. NPS tow tank facility

B. PROTOTYPE DESIGN USED

The bubbler has four tentacles made from aquaculture bubble hose. Each hose was 25 cm long and approximately 12.5 cm apart. The manifold that the hoses were attached to was made from machined aluminum (Figure 9).

Figure 9. NPS 1/100 scale Bubble Squid

Air was supplied to the bubbler using compressed shop air from the Spanagel Hall building. It can be seen in Figure 8 how the hose supplying the air

is run along the yellow stanchion to the Bubble Squid in the water at the base of the stanchion. During experimental test runs a flow meter was installed between the shop air line and the bubbler to gauge the true air flow rate (Figure 10).

Figure 10. Flow meter (left) and air hose attachment to shop air (right)

C. PROCEDURES

The following sets of data runs were collected from March 8, 2010 to March 12, 2010. The first morning was used to make sure the Templeman Automation personnel were allowed on the NPS base and all of the equipment as well as the NPS tow tank were in working order. Much of the morning and afternoon were devoted to making a bracket that we could use to hold the pressure sensor off the bottom of the tank and just below where the Bubble Squid would be traveling. Figure 11 shows the carriage that was fashioned to hold the pressure sensor off the bottom of the tow tank. It was constructed from parts that were available from the NPS mechanics shop.

Figure 11. Pressure sensor carriage

Once the carriage was built and the pressure sensor was mounted, the unit was lowered into position inside the tow tank approximately halfway down the tank in the X direction (about 10.5 feet). For the first day of data collection, the height of the Bubble Squid and the pressure sensor depth were not varied. Our group was able to accomplish 22 runs at varying speeds with and without air flow. These first data runs were taken with the Bubble Squid six inches above the sensor during those data runs.

Day two of testing was an early morning start, because equipment setup was completed the previous day. Once the equipment lineup was verified, data runs were commenced. Data runs 23–47 were performed the same as the first set, varying speed as well as performing with and without air flow. Once we were satisfied with the data we had collected at this height above the sensor, the pressure sensor was removed from the carriage and placed onto the bottom of the tow tank. The height of the Bubble Squid was adjusted so that it would make data runs at a separation height of 14 inches from the pressure sensor. However, The installed gantry crane system and yellow stanchion would not allow for data

runs at the depths our team was looking for. To accomplish this separation height an extension bar was made to attach the yellow stanchion at the center of the gantry rail system. Eleven data runs were collected at 14-inch separation with varying speed and air flow. Then the Bubble Squid was lowered again for a 4-inch separation and eight runs were completed at varying speeds and air flow.

Day three saw the largest amount of data collection during the entire week. Seventy-seven different runs were completed at varying heights above the sensor and some also performed without the extension bar created the previous day. Our intention on this day was to collect as much data as possible that would show how the pressure drop decreased as the Bubble Squid was separated from the pressure sensor by height.

Day four started with a realization that we had collected all of the data that was deemed mandatory before the week's experiments were started. Because we had two more days reserved with the tow tank, adjustments were now made to the Bubble Squid itself. The decision was made to change the hose lengths from one-foot long hoses to three-foot hoses. This change in hose length allowed for collection of some data that had not been anticipated to be collected until the DTMB testing. Eight different runs were completed using these longer hoses. Data collected with the three-foot hoses showed significant differences from the one-foot data runs. It was decided that a more accurate measurement of air flow from the shop air lines was needed. A McMillon flowmeter was then attached to the shop air line. Twenty-three more runs were completed with the longer hoses and the high accuracy flow meter installed. The data provided from these runs was found to be the most useful for analysis. The results will be provided in Section D of this chapter.

The final day of testing was used to perform some static testing above the pressure sensor with air flow set at the shop air maximum. There were also a few data runs performed at varying heights. With the understanding that all of the data that was needed had already been collected, the final day ended relatively early, which allowed time for cleanup of the equipment and the tow tank

facility. There were an enormous amount of tools and materials that all needed to be wiped clean and dried, prior to being returned to the proper owners among the professors in the basement of Spanagel Hall. A detailed breakdown of all the data runs is in Appendix A.

D. RESULTS

The first experiment conducted was an evaluation of the flow range achievable with the facility air, and a measurement of the bubble rise speed associated with various airflow rates supplied to the Bubble Squid. This was accomplished by timing the rise of the bubbles from the initiation of air (using a ball valve at the shop air feed) to the cresting of the bubbles at the water surface. The Bubble Squid depth for these tests was approximately 70 inches (1.77m). The results from the first set of data collection runs are shown in Figure 12.

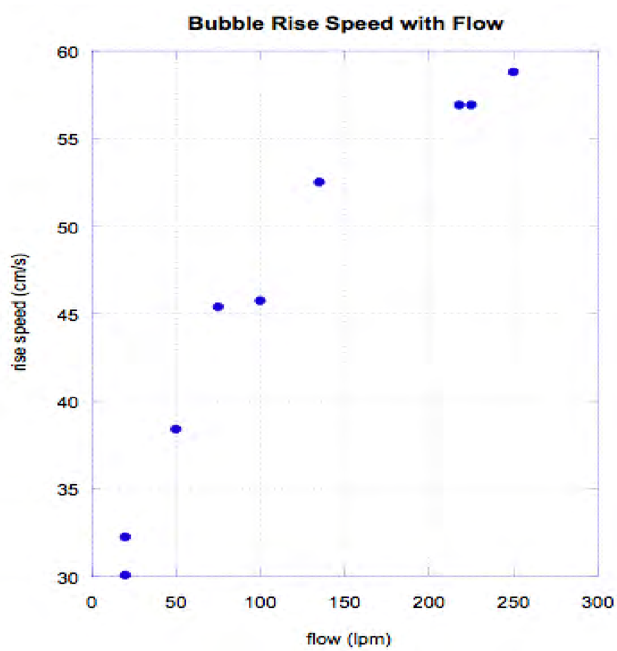

Figure 12. Bubble rise speed tests

Several aspects can be established from the plot in Figure 12. First, it should be noted that the rise speed shown represents the fastest bubbles, as the

rise time was measured between start of air flow and first cresting of the bubble plume as seen at the surface of the tow tank. Also, the flow rate shown represents an averaged value as the flow meter was slowly varying and a reciprocating piston compressor supplied the compressed air to the Bubble Squid. Therefore, the flow rate may have been varied from somewhat less to somewhat higher than those shown at a rate of several liters per minutes. There was some visual indication that this was the case. The rise speed observed in testing was significantly faster than what was expected based on published bubble rise speed data. This was likely because the resultant bubble size of the fastest bubbles was very large (>3cm). Large diameter bubble size was a regime not well covered in any of the theory research literature studied prior to testing. Smaller bubbles certainly were created and observed throughout testing, however it was very hard to determine what the approximate bubble size distribution was. The rise speed for low flow conditions was found to agree well with published values, and visual observations suggest that the bubble size was more homogeneous and smaller below an air flow of about 50 liters per minute. Based on the flow rate and the rise time measured, the void fraction can be calculated above the Bubble Squid in a very simple way. Using the Bubble Squid area to be a simple product of the hose length and the total width of the manifold, the void fraction is shown in Figure 13.

Void Fraction = (Air Flow Rate) / (Bubbler Area * Rise Speed)

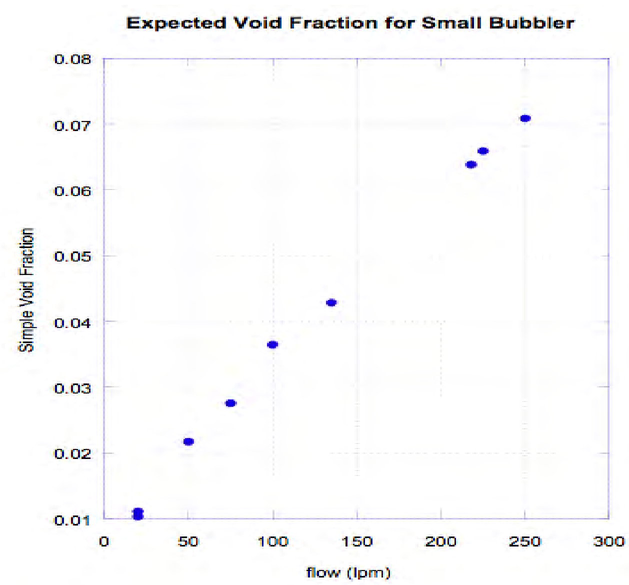

Figure 13. Expected void fraction for Bubble Squid

The critical result that can be inferred from Figure 13 was that the void fraction above the Bubble Squid was low compared to the expected theoretical maximum. This plot suggests that increasing the air flow should continue to increase the void fraction and, therefore, reduce the resultant pressure signal. This would seem to be supported by a simplistic hydrostatic model in which increased void fraction produces a larger pressure drop within the water column. A dynamic model in which more upwelling bubbles results in an increased upward circulation, would also serve to reduce the pressure sensed below the upwelling due to water movement in cycling vortexes.

It should be noted that the limits on void fraction in open, deep water, as compared to a laboratory cylinder, are speculative. For the Bubble Squid concept the dynamics of the bubble plume is of paramount importance, as more air creates both upwelling and horizontal flow circuits within the water column. Visually, it appeared that as air flow is increased the transverse dimensions of the bubble plume produced from the Bubble Squid are also increased. This suggests that for the testing to be performed in the DTMB tank, increasing the air flow might not increase the total void fraction over the Bubble Squid, but rather

create a more rapid expansion of the bubble plume. In a dynamic model of the pressure signature, this would still suggest that there is a greater pressure effect with increased air flow. But it may not increase the total pressure drop as much as extend the transverse extent of a more modest pressure drop. It was also determined that there was a possibility, as testing moved into Phase II, that the true void fraction was greater than that shown in the smaller NPS tow tank tests due to the presence of slower rising bubbles in the plume. Additionally, the void fraction is not constant throughout the bubble plume because the water very close to the Bubble Squid hoses is not uniformly filled with bubbles.

To test the effect of flow rate on the pressure signature below the bubbler, thirteen runs were performed with various air flow rates. For all the runs the tow speed was held constant at 0.33 m/s and the separation between the bubbler and the sensor was likewise constant at about 37 cm. Figure 15 shows the pressure signature for twelve data runs with air flow rates between 50 and 250 lpm. All NPS data runs were first referenced to the pressure effect without any air running through the Bubble Squid. A pressure signature was still obtained in each of these “dry” runs. It is perceived that this pressure signature was caused by bow shock from the Bubble Squid manifold and circulation caused by the tow carriage and Bubble Squid traveling through the tank at speed. However, in all the “dry” runs, the pressure signature was always smaller and of shorter time extent than when air was on and bubbles were being produced. The surprising result was that while at very low flow the pressure signature approached the “dry” values. At even modest flow (> 50 lpm) this effect was very repeatable.

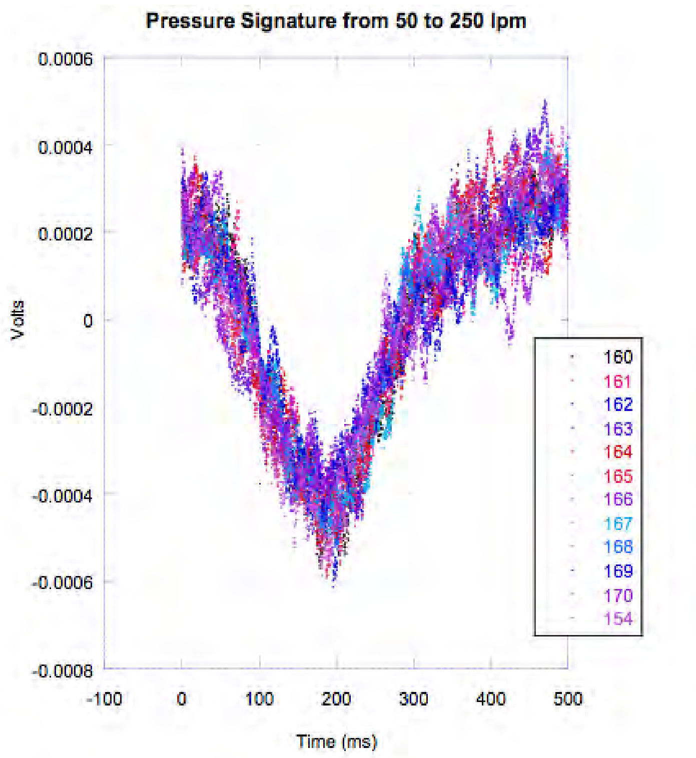

Figure 14. Pressure signatures for 12 run data series of varying air-flow rates. Legend indicates data run number.

The correspondence of both shape and size between these runs was surprising. There was a small, systematic shift in the maximum pressure drop observed with air flow change, but it was much smaller than our group had expected given the wide range of air flow values at which these data runs were performed.

To further analyze the functional relationship between air flow rate and maximum pressure signature, the pressure peak value was established for each run and plotted versus the flow rate (Figure 15).

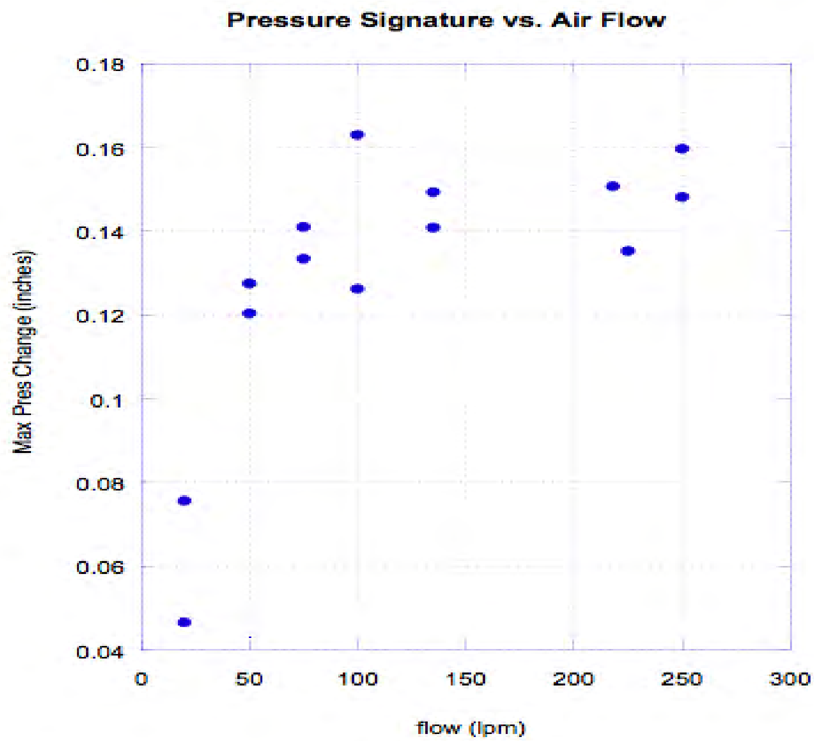

Figure 15.   Maximum pressure effect over range of air flow rates.

In Figure 15, we see a rapid increase in pressure drop corresponding to increased air flow. It is also easy to see this effect level off over air flow rates of about 75 lpm. It should be noted that this data was normalized such that zero flow yields zero pressure effect, and this was performed even though it was understood that there are some pressure fluctuations due to the Bubble Squid traveling through the tow tank during data runs.

Referring back to Figure 13, it can be seen that the simple void fraction expected for an air flow rate of 75 lpm is about 0.028, or about one-tenth the expected maximum void fraction that was attained during static tank laboratory testing. This suggests that limitations of the void fraction through mechanisms seen in the laboratory with a constrained water volume are not to blame for the reduction of the pressure effect, unless the void fraction was actually much higher due to slower bubble rise velocities than what was measured. There may be a dynamic situation where the lateral force on the bubble plume from the

Bubble Squid spreads the throughout the extent of the plume, which would effectively limit the total void fraction above the pressure sensor.

Whatever the explanation for the observed pressure discrepancy, a void fraction of about 0.36 was set as the goal for the 1/10 scale Bubble Squid to be used in the DTMB testing. It may be more applicable to consider the maximum air flow per foot of Bubble Squid hose. In this case we use the value of about 75 lpm. because it achieved the maximum pressure change. The total bubbler hose length used was 1 meter (25 cm X 4). Therefore a value of 75 lpm/meter was used as the figure of merit for the building of the DTMB Bubble Squid.

V. DAVID TAYLOR MODEL BASIN TESTING

A. FACILITY SPECIFICATIONS

The David Taylor Model Basin (DTMB) is located at the Naval Surface Warfare Center, Carderock Division, in West Bethesda, Maryland. The following information was taken from the American Society of Mechanical Engineers January 30, 1998 article. This model basin was built in late 1930s and was dedicated on 4 November 1940. The model basin is still in today use by the U.S. Navy, and is considered to be one of the largest model basins ever built. In 1998, the facility received the Historic Mechanical Engineering Landmark designation for the American Society of Mechanical Engineers. Having spent over a week at this facility performing test runs with the Bubble Squid, it is no small wonder why this facility has received so much praise and distinction.

The testing facility houses four different test model basins with six different tow carriages. The test basin used for our experiments for the Bubble Squid was the largest tow basin on the facility. It is called the large deep-water basin and is 1,886 feet long, 51 feet wide and 22 feet deep. The number two carriage for this basin is steam powered and can maintain sustained speeds up to 20 knots with an accuracy of ± .01 knots.

What makes this basin remarkable is the accuracy to which it was constructed. For accurate speed testing, and to maintain precise constant height above the water, the rail system that each carriage travels on was laid out to correct for curvature of the earth. This correction for curvature of the earth is used to remove gravitational effects on the motion of the tow carriages. The model basin is traditionally used to test hull designs prior to shipbuilding of a new class of naval vessels.

B. PROTOTYPE DESIGN USED

Because the Bubble Squid project had transitioned into the Phase II portion of funding through ONR, the model was required to be 1/10 (3 meters) of

the eventual model requested. This required the building of a three-meter wide by three meter long Bubble Squid. The Bubble Squid hoses for this model were adjustable to any length of hoses up to and including three meters in length. A computer-generated prototype Bubble Squid is shown in Figure 16.

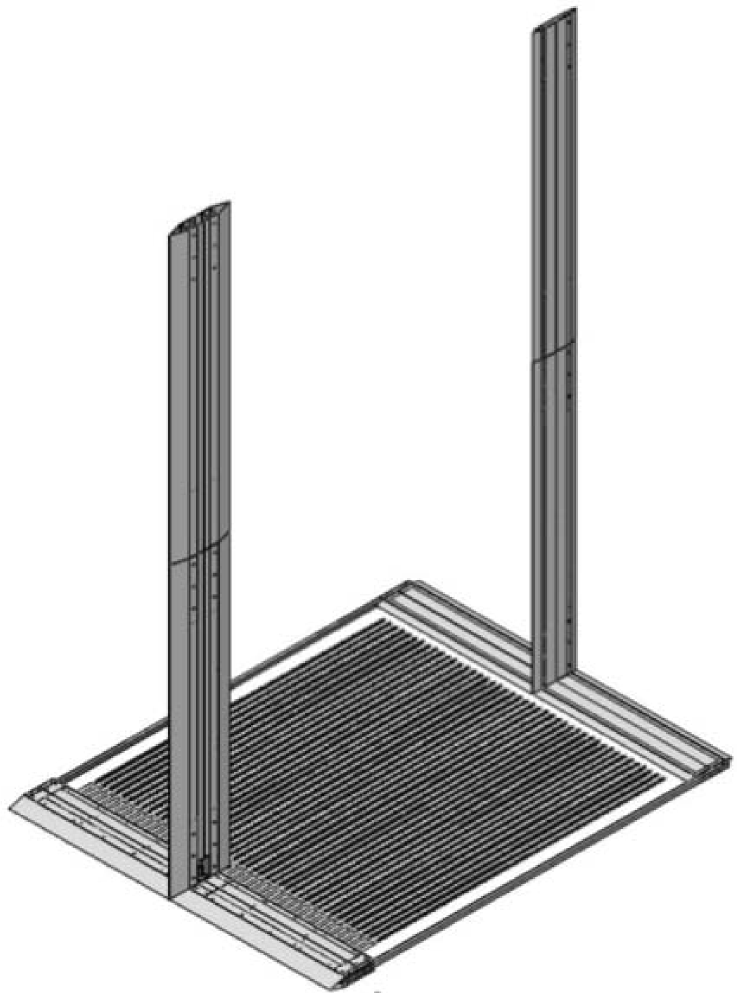

Figure 16.   1/10 scale Bubble Squid design for DTMB testing

This Bubble Squid design consists of 44 bubble tubes separated by approximately 6 cm. The hoses used were constructed of the same material used for the Phase I testing, which was the sintered rubber soaker hose.

For DTMB testing three different hose lengths on the Bubble Squid were used. Some testing was also performed with bubble tubes plugged for no air flow. The air distribution system was designed so one set of hoses could be easily removed and a new size of hoses reattached on site in a timely manner. The goal was to be able to remove and replace hoses at the test site in a short period of time and possibly while the device was still connected to the overhead carriage system during tow tank testing. This was essential to our testing because of the extreme cost involved with using this test facility. The same concept of using tube fittings and hose clamps used in the Phase I proved to be adequate for use on the 1/10 model Bubble Squid. The stabilizer arms shown on each side of the tow vehicle are intended to hold guide wires to ensure that the bubble hoses remain at fixed distances from each other as well as remain parallel to the bottom of the tank. Figure 17 shows the distribution of air supply for the 1/10 scale model at three hose lengths.

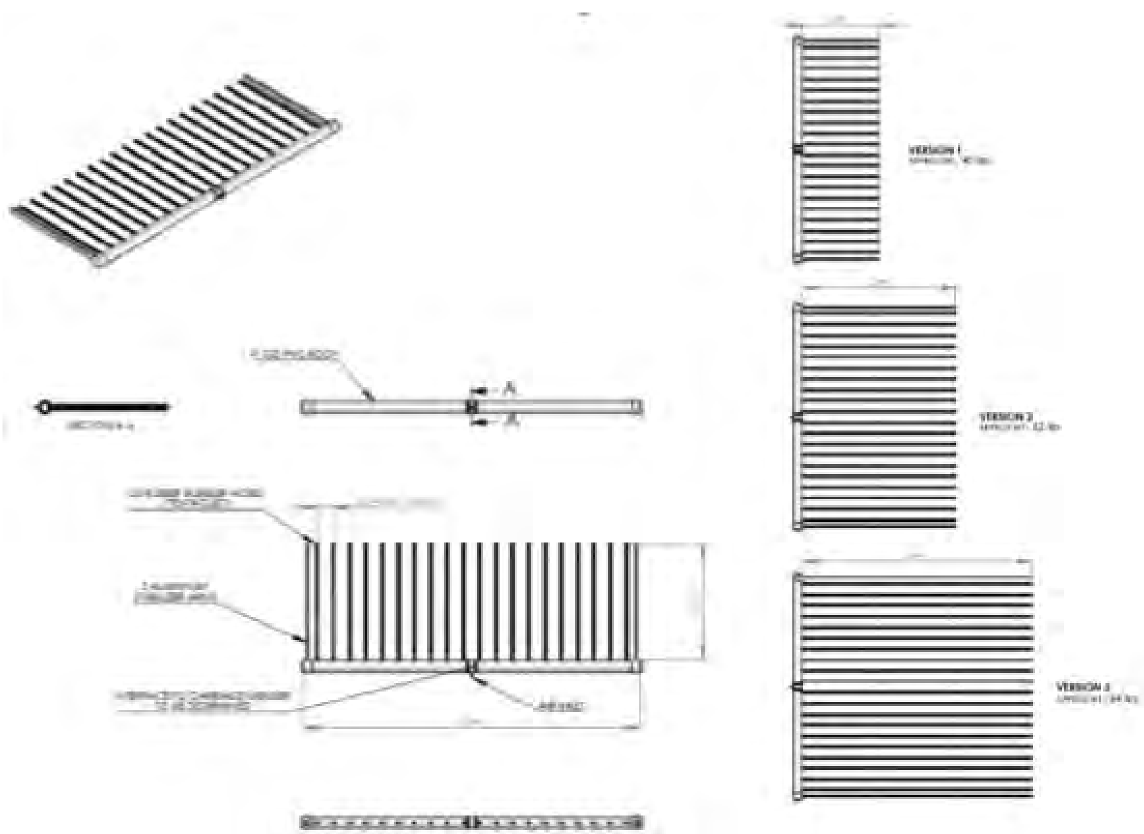

Figure 17. Air distribution system for 1/10 scale Bubble Squid

For cable towing, a more hydrodynamic device would be required. In order to reduce drag during towing, a cowling was added to create a ‘tear-drop’ shaped structure with hoses protruding from the narrow point of the teardrop. Further, the buoyancy and depth control also was addressed. Initial buoyancy calculations were made using a ‘chain dragging’ depth control system.

For DTMB testing the tow vehicle was rigidly mounted onto the #2 tow carriage. A frame to carry the Bubble Squid was designed and manufactured for TA, prior to the May testing. The first frame was designed so that there would be little (less then a 2”) flexure under gravity without any buoyancy aid. This was a conservative estimate considering that during testing the Bubble Squid and supports were aided by buoyancy. Drag calculations were made, and it was determined that a more streamlined designed had to be constructed. The largest contributor to the test setup was the main vertical beam used for holding the vehicle at depth in the tow tank. Because it was known that the deepest the Bubble Squid would be was 20 feet deep at 10 m/s, a drag calculator was developed in order to test various configurations. Simple pipes and other tubular configurations couldn’t carry the necessary loads without unacceptable (greater than 2 inch) flexure. These results made it necessary to build the larger Bubble Squid and its carriage unit from high strength steel.

1. Air Supply Considerations

Specification of an air supply was a key decision to the success of Phase II program. The air supply (air compressor) had to be adequate to produce the desired pressure signature at all depths. Our team decided to choose an air compressor large enough to provide the air volume required to produce a void fraction of one and quarter times, amount of air required per unit hose length, the greatest void fraction in the 1/100 scale model tested at NPS. This requirement would be a 0.036 void fraction as discussed at the end of chapter 4. This value was chosen because it was assumed to be the practical limit as was discussed between Dr. Bruce Denardo (NPS Professor) and the TA group. For tow tank

testing in Phase II the largest bubble generating area employed was nine square meters. Assuming a bubble rise of 0.2 m/s, the volumetric flow of air needed to produce the maximum void fraction was approximately 30,000 liters per minute (l/min) or approximately 1000 cubic feet per minute (ft^3/min). The tow tank maximum depth (22 feet) corresponds to a pressure of 9.5 psig. Based on discussions with an aquaculture expert, a pressure head of 5 psi above water pressure is sufficient to generate bubbles through aeration hose (Private communication with Allan Tweten of Aquatech Environmental Systems Ltd. with TA). Therefore, our air supply had to supply a minimum of 14.5 psig to cover all depths that could be tested at the DTMB tow tank. Choosing the right air compressor to meet this minimum air supply was important to our collaboration team because we understood that the intended deployment vessel for open ocean testing with a Bubble Squid was the 11m RHIB (Rigid Hull Inflatable Boat) which has a maximum weight capacity of 3200 lbs. The tow carriage at DTMB did not have this same weight limitation, however an effort was made to be forward-looking and keep in mind the restrictions of the Phase III open ocean testing. An additional benefit to selecting a lighter air compressor is the ease of positioning at the test basin, which reduced the amount of time spent during setup.

Another forward-looking issue, that was of concern for choosing the air compressor, dealt with power requirements. Twin Caterpillar 470 hp engines power the standard Navy RHIB. While the maximum speed of this vessel is greater than 45 knots, the top speed determined for towing of the Bubble Squid was anticipated to be only 20 knots. So the air compressor chosen would only be able to draw a certain amount of the total 940 horsepower that can be delivered by the RHIB's engines and still provide enough horsepower to achieve 20 knots while towing the Bubble Squid. Forward-looking or not, the power requirements of the air compressor chosen also had to be met by the power supply capabilities of the DTMB tow carriage, not to mention having to solve how to mount the air compressor to the tow carriage. In the end the power (or more

clearly the current) limitations of the tow carriage were more stringent than what could be supplied by the RHIB engines. This afforded some luxury in knowing that if the air compressor chosen was sufficient during DTMB testing then it would be sufficient for initial Phase III testing. The issue of mounting the compressor was solved by the workers from the DTMB facility who were able to manufacture and install mounting plates for the air compressor on the upper end of the tow carriage.

Initial Phase II lead-time allowed for a thorough survey of companies that produce industrial air handling equipment that could be used for the Bubble Squid concept. Kaeser, Gardner-Denver, and CompAir were the three companies that were evaluated for providing the equipment needed for the air supply. Each company was found to posses air handling equipment that was sufficient to meet our air requirement specifications. The Phase II program included funding for further research into the compressors that would be required for follow-on Phase III testing. The best candidate found during research was the use of a rotary screw compressor airend. The airend is the part of the compressor that contains the rotary screws that actually compress and direct the air. This would be beneficial because it would eliminate the need for a dedicated motor for the unit, which significantly reduces the size needed onboard the RHIB. The weight reduction of using only an airend as opposed to an entire compressor could be as much as 50%, while still allowing the vessel to achieve the required speeds for minesweeping.

The final selection for the air compressor used during DTMB testing was the VS70 screw-drive compressor from Gardner-Denver (Figure 18). This compressor had a maximum flow capacity of about 11,000 lpm, which was about 45 times the flow rate available from NPS Shop air. The compressor was variable speed, which allowed for continuous adjustment of the air flow. Because the compressor chosen was a screw-drive compressor, it would be able to provide

more consistent air flow to the Bubble Squid as compared to the reciprocating piston compressors that were used at NPS to provide the shop air during previous tow tank testing.

Figure 18. Gardner-Denver VS70 screw type air compressor

Larger compressors were available, but as stated previously the current limitation from the tow carriage at DTMB was the limiting factor for the overall compressor size. Based on the capabilities of this compressor, Table 1 compares the NPS Bubble Squid and the three variations of the DTMB Bubble Squid based on the liters per minute per meter figure of merit described in the previous chapter.

Bubble Squid	Total Hose Area (cm^2)	Total Hose Length (m)	Max Air Flow (lpm)	Max lpm per meter
NPS	1,000	1	250	250
DTMB - 1 m	30,000	44	11,000	250
DTMB - 2 m	60,000	88	11,000	125
DTMB - 3 m	90,000	132	11,000	83

Table 1. Air flow figure of merit for Bubble Squids

Reviewing Table 1, it can easily be seen that the smallest hose size for the DTMB Bubble Squid had identical lpm per meter capabilities as the NPS model, but on a much larger scale. Additionally, even the largest hose size (3m) has a air output per meter of hose rating in excess of the 75 lpm/meter cutoff for increasing the pressure signature found during tow tank testing at NPS. These combinations of compressor and Bubble Squid geometry allow for a full characterization of the effects of air flow on the pressure signature that should be seen on the 1/10 model scale. In retrospect, a larger compressor would have been beneficial for creating larger pressure signatures, but such a compressor for use on a RHIB would have not been viable.

Another critical element of the scale-up theory was the persistence of the bubble perturbation of the quiescent pressure field. According to the transfer-function theory used by ocean wave measurement systems at the sea floor, the penetration of a pressure signature near the surface to the seafloor was highly dependent on the frequency band of the pressure fluctuation. In this theory, longer lasting pressure waves propagate to the sea floor much more efficiently than rapid perturbations. In the case of the DTMB testing, the tow carriage has a maximum speed of about 10 m/s (20 Knots), compared to the maximum speed at NPS of 1 m/s. The overall size of the tow basin and the speed of the tow carriage allowed for testing over a much wider range of time durations as compared to what was achievable in the NPS tow tank. This allowed for a full characterization

of the depth penetration theory developed earlier for the Bubble Squid and also for some direct comparison to the results gathered during NPS 1/100 scale testing.

C. PROCEDURES

The ability to achieve the required performance parameters for the Bubble Squid system is governed by numerous design parameters. While some of these parameters are static, others are variable. The values of some variables may depend on others. Using the static variables (e.g., tank depth, width and length) as a guide, a comprehensive test matrix that covers all permutations of variable parameters was determined to be time consuming and not be cost effective. Reducing the test matrix to a manageable collection of variables was necessary and definitely resulted in a more focused effort during our small test window at the DTMB facility.

All of the deep-water basin tank parameters are essentially static. Carderock personnel provided guidance prior to our testing that the tank level can be lowered and raised. However, based on the required time for level changes and time scale of the test series this was not attempted.

The goal of the DTMB testing was improve on the results of our 1/100 scale Bubble Squid, while also trying to meet the baseline requirements set forth by ONR. Advice from one Navy POC from Panama City suggested that our tests should focus on measuring the pressure signature at the bottom of the tank. Bottom measurement made the most sense for practical applications considering pressure-actuated mines are most commonly bottom (seafloor) mines. Therefore, sensor depth was considered to be a static variable. It should be noted that in Phase I tow tank testing some data collection runs were performed with the pressure sensor off the bottom of the tank. If the pressure signature observed at the tank bottom was significantly different than what was seen at NPS, variation of sensor height might have been an additional area to investigate. It was articulated to our team that the DTMB facility had a scissor

jack that could be used to adjust sensor height. However for our testing it was determined that moving the sensors off the bottom of the basin floor would not be required. Instead it was decided to mount all of the pressure sensors onto PVC pipe structure that was attached to a large ladder that would provide additional weighting to the structure. The sensors were laid out in a manner that could measure the pressure drop across a width greater than the Bubble Squid (Figure 19). The additional weight was needed to prevent the pressure sensor structure from turning over or moving during each data run.

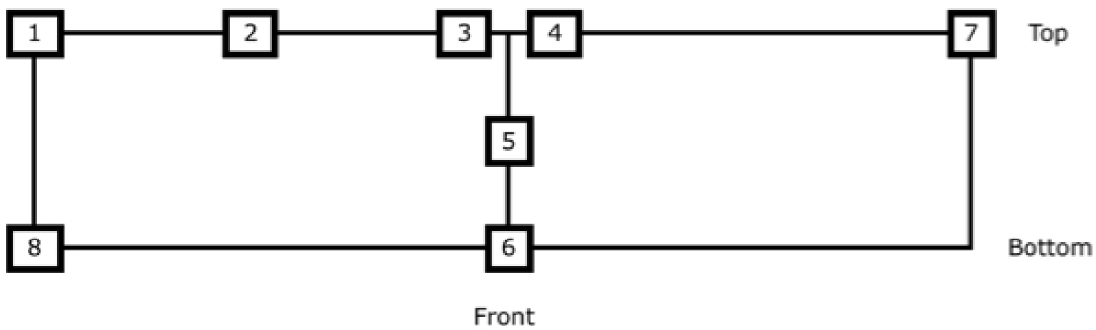

Figure 19. Pressure sensor layout on DTMB sensor bar

There were four main parameters concerning the geometry of the Bubble Squid, each of which may have had an effect on the magnitude of the pressure signature recorded and the duration of the pressure signature observed. However, changing the array geometry as part of the testing at DTMB could have been proven too difficult and time consuming. So the initial experiments at Templeman Automation LLC and NPS were used as much as possible to determine which of these parameters are critical. This was useful to help isolate the optimal configuration for the 1/10 Bubble Squid used during laboratory testing. Most important were the critical values for hose spacing.

As stated previously, the Bubble Squid hoses were constructed out of a porous material. Size of the pores in the hosing affects the bubble size. Using the results from flow tank testing performed at NPS during 2009, the configuration

that had the greatest separation while maintaining a constant pressure drop was used (6 cm). Bubble Squid hose configuration was fixed at 3 meters, which was the entire model width. This was chosen because it was believed to be sufficiently large enough to ensure the edge effects of the Bubble Squid, if any, are negligible. This width would also keep the Bubble Squid small enough, with respect to the tow tank width, so that that the tank walls would not influence the results garnered during testing. The width of the bubble generation was able be varied through the use of individual plugs that shut off flow to any hose position selected.

The duration of the pressure drop was the key parameter that our team was determined to measure during DTMB data collection. Because it was known that hose length of the Bubble Squid may influence this effect, the three different hose lengths were built and brought to the DTMB facility for our test runs. As stated before hoses were fabricated with one, two and three meter lengths. The Bubble Squid was designed such that hose change-out and plugging or unplugging could be accomplished without the need to remove the unit from the carriage, thereby saving time during testing. Each configuration was tested to determine the effect that hose length had on the pressure signature recorded by the sensor bar.

1. DTMB Test Towing Parameters

All parameters in this category were varied to determine their effect on the pressure signature. Air pressure and volume are important parameters because the pressure and volume requirements necessary to make an adequate pressure signature will define the type, size and weight of the deployable air delivery system. For DTMB test setup, the input pressure from the compressor determined the Air Volumetric Flow rate. A pressure regulator valve was placed on the outlet of the compressor to lower the output pressure to the different levels used during test runs. In the test matrix the convention using 0-100% of the compressor's output pressure (before regulating) will denote this link of volume

and flow rate. Based on the discussion above, the parameters that will be varied as part of the DTMB test matrix were: Bubble Squid Depth, Tow Speed, Air Pressure, Hose Length and Bubble Generation Area.

2. DTMB Testing Objectives

The objectives of the testing were: (1) Replicate pressure drop achieved in Phase I, NPS tow tank testing, (2) Characterize the pressure drop as a function of depth, (3) Characterize the pressure drop as a function of tow velocity, (4) Characterize the pressure drop as a function of air pressure and volume, and (5) Characterize the pressure drop as a function of hose length.

Thankfully during the two weeks of testing at the DTMB all of the objectives mentioned above were accomplished. Data runs began on May 17, 2010 and were concluded on May 26, 2010. During that timeframe 322 data runs using 18 different configuration changes were completed. The changes involved the Bubble Squid height above the sensor bar, hose length and number of hoses attached. Each configuration also included performing runs without air, with full air and varying air sent into the Bubble Squid. A full detailed breakdown of the data runs accomplished during DTMB testing is in Appendix B.

D. RESULTS

Based on the extensive data runs performed by our testing group at the DTMB, data reduction and analysis was performed to present the acquired data. The goal of this analysis was to develop a simple theory describing the pressure signatures observed at the David Taylor Model Basin during the three-week Bubble Squid test series there between May 9 and May 28, 2010, and to use this theory to predict the scale-up requirements for a full-scale mine-sweeping device based on Bubble Squid technology. Figure 20 provides a visual display of the 1/10 scale Bubble Squid apparatus during one of the many test runs completed at the DTMB.

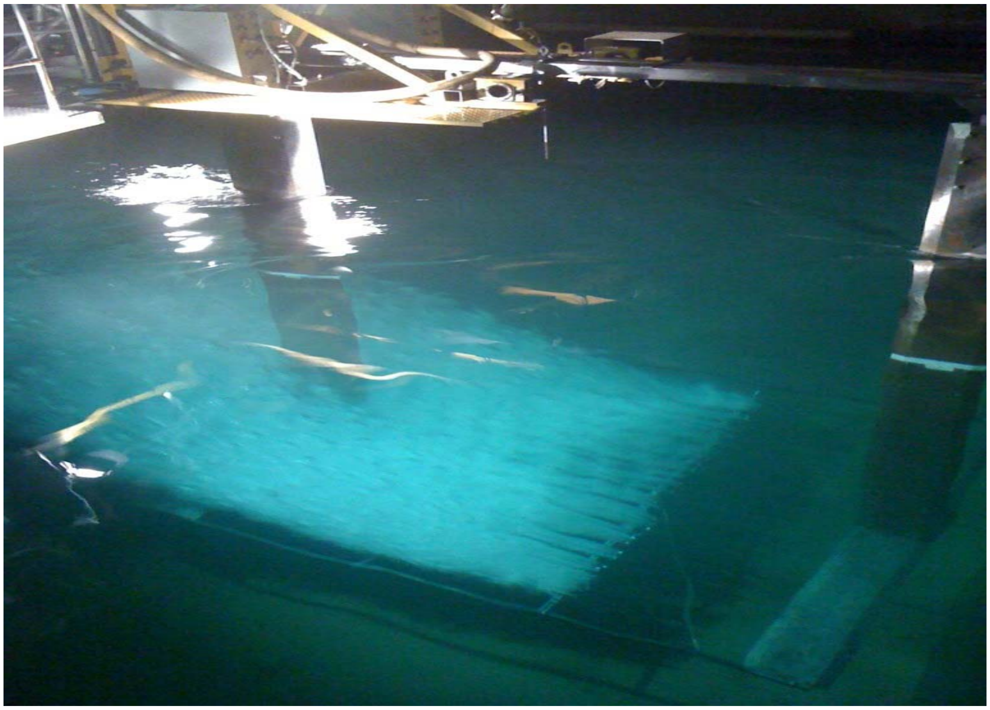

Figure 20. Bubble Squid in operation at DTMB

Based on the data collected, a generalized pressure signature shape was generated (Figure 21). The goal of this initial data analysis was to evaluate the key elements of the pressure signal, shown in Figure 21, for use in a mathematical scale-up model our group named BSQ (short for Bubble Squid). The intention of the BSQ model was to establish reasonable parameters for a full-scale system used in open-ocean testing if funding was provided to move on to Phase III testing. BSQ was written by the TA group to function as a spreadsheet document with user-definable tow speed, required pressure threshold, required dwell time below threshold, air flow rate, etc. BSQ was intended to only include the bubble-induced pressure signature and does not provide any attempt to try and recreate the possible shock effects associated with any of the Bubble Squid hardware passing beneath the surface. This was chosen because the effect of hardware components is expected to be negligible in a full-scale Bubble Squid operating in the open ocean environment.

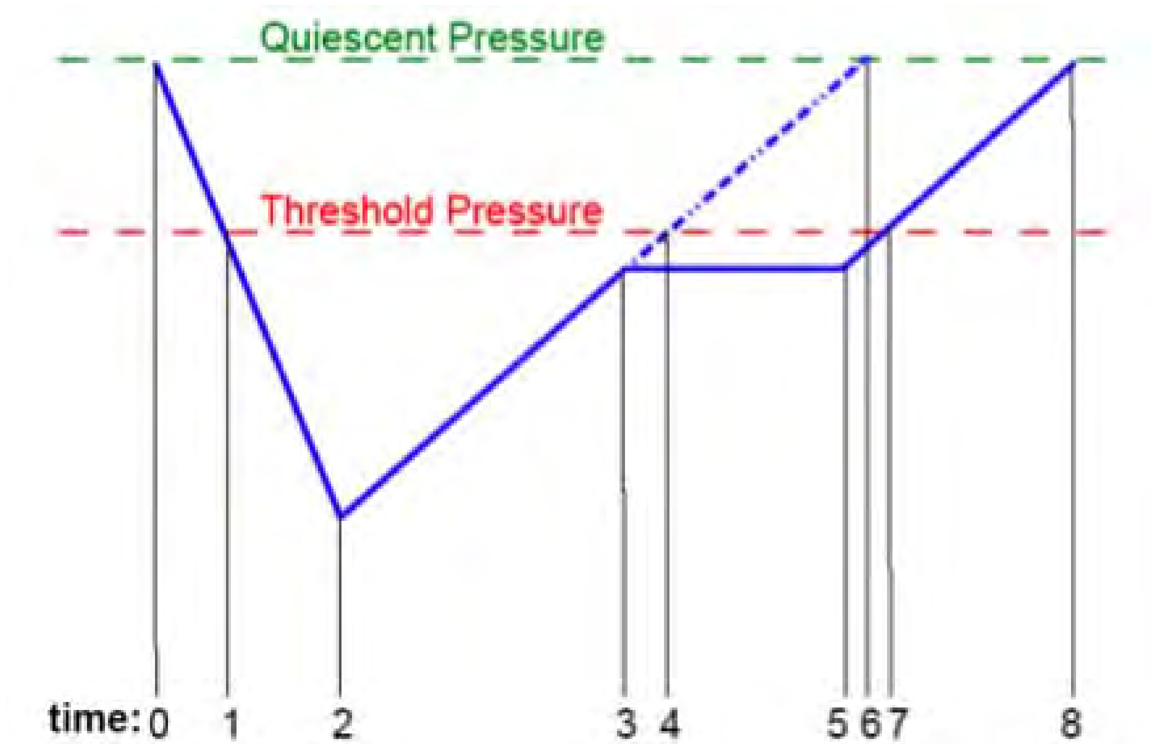

Figure 21. Pressure signal observed at DTMB, used for modeling as the signal elements for the BSQ program

Table 2 provides a descriptive breakdown for each of the numbered time steps seen above.

Time	Event
0	Start of event at the pressure sensor
1	Pressure first crosses the threshold value. For minesweeping the threshold is found to be roughly a 1-inch seawater head.
2	Pressure drop peak, maximum pressure change
3	Pressure peak levels out to a sustained equilibrium pressure drop. This could be caused by extended dwell time of the Bubble Squid hoses over the pressure sensor area.
4	In the absence of extended dwell time of the Bubble Squid over the pressure sensor, the decay of the initial pressure drop returns to the threshold value.
5	For long hose lengths: Bubble Squid has passed clear of the pressure sensor and bubble effect begins to decay as the bubble plume rises away from the sensor
6	Pressure drop is no longer present, pressure has returned to the quiescent start value
7	For long hose lengths: Decay of the initial pressure drop returns to the threshold value
8	For long hose lengths: Pressure drop is no longer present, pressure has returned to the quiescent start value

Table 2. Pressure signature time step breakdown

The goal, then, became trying to establish a generalized pressure model. This was started by approaching the data acquired from the DTMB tests with an aim towards building a mathematical form corresponding to the key time steps from Table 2. The data shown in Figure 22 represent pressure signals seen from data runs performed with full air compressor continuous air delivery, with the Bubble Squid being towed at a variety of speeds over the pressure sensors. The

output shown below is from only a single, central pressure sensor. Only one of the central pressure sensors was chosen because, over the total of all signals received from the eight pressure sensors used, the variation between the different sensors was found to be only modest.

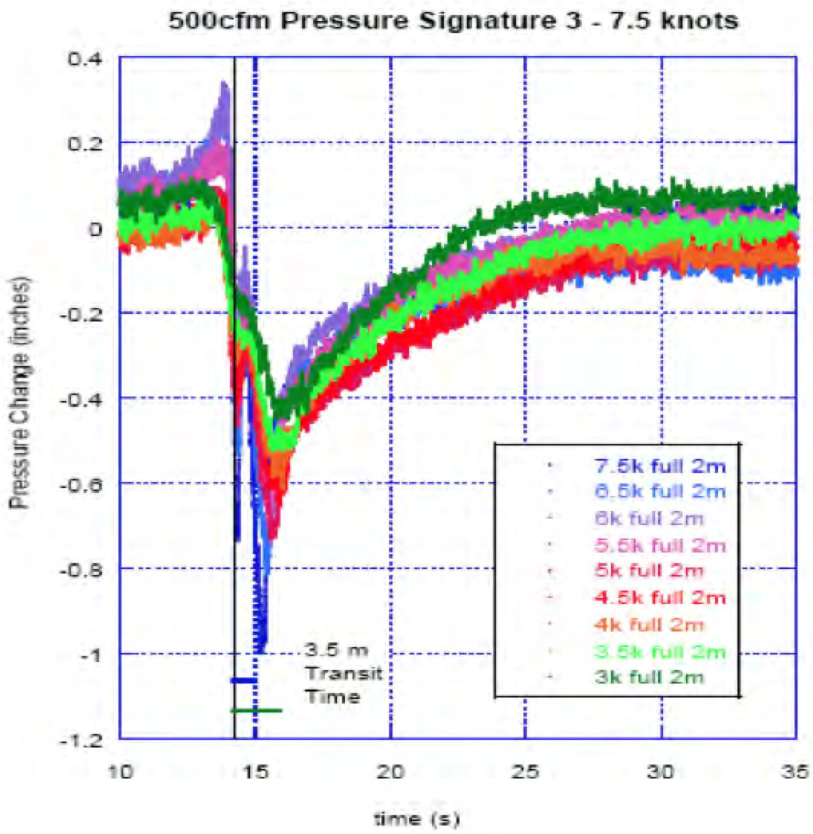

Figure 22. Pressure signals for full air runs with 2 meter Bubble Squid hoses at varying tow speeds

The data shown in Figure 22 also represents the highest continuous air flow achievable during the testing due to limitations of electrical current that could be supplied by the tow carriage at the DTMB. The traces have been aligned based on the location of the stanchions. This gives all the runs a standard orientation in time with respect to the pressure sensor.

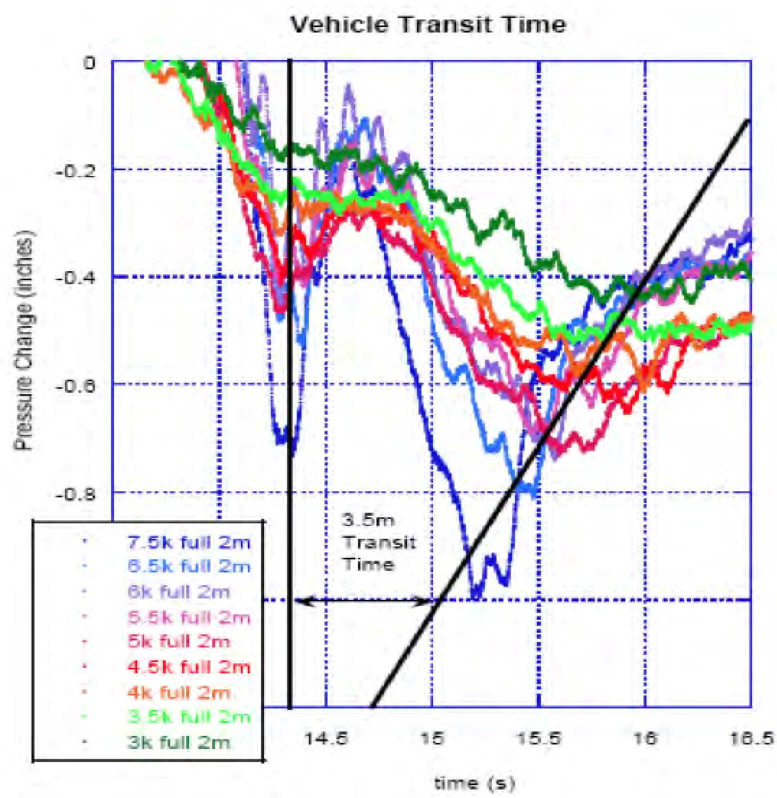

Figure 23. Pressure spike caused by Bubble Squid stanchions

The traces are aligned on the front stanchion, so the rear stanchion varies according to the tow speed as seen in the right side of Figure 23. The nominal distance between the stanchions was 3.5 m and this was reflected in the plot. Several key features can be observed from Figures 22 and 23:

1. Above a tow speed of 3 knots, the shape of the pressure signal was very similar.

2. The key difference between speed runs was directly related to the high-frequency stanchion shock events, and was seen in no-bubble runs as well.

3. The majority of both the lead-up slope and decay curve occur outside the time in which the array was actually above the sensor.

4. The decay slope, which was related to the ascent of bubbles after the array transit, was remarkably similar over the speed range.

For much slower tow speeds, between 0.5 and 2 knots, the leading slope changes somewhat, however, a direct comparison was complicated by the disappearance of the effects from the front Bubble Squid stanchion of the pressure signature observed. The slower tow speeds were found to not be particularly relevant from an operational perspective, however they may give insight into the effects of having longer hose lengths of the Bubble Squid apparatus that would have a significant dwell time over the pressure sensor.

1. Air Flow Profile Analysis

The relationship between the pressure signal and the total air flow applied to the bubbler array was critical for analysis of scale-up. The air compressor used during DTMB testing maintained continuous air delivery around 500 cfm at operating pressures. Based on analysis of data previously acquired during testing performed at NPS, an air supply of at least 1000 cfm was anticipated to be necessary to reach the operational goal of a 1- inch pressure drop. Therefore, to try to increase the range of testable air flow settings, an accumulator tank had to be attached to the tow carriage next to the 500-cfm compressor on the tow carriage to allow greater air flow over a short time period by charging the accumulator tank and releasing the pressure to the Bubble Squid using a manual valve. This allowed the later data runs to reach higher peak airflow (and peak pressure) values, but only for a limited time. This limited time of peak air flow was found to complicate the overall pressure profile analysis. However, the use of this system did allow the apparatus to achieve operational-scale pressure changes up to a 1.5 inches of head peak pressure change, one-half inch greater than what was required in the initial demand from ONR for the Bubble Squid concept.

The first step towards understanding the effect of air flow on the pressure signal was to evaluate the time-varying air flow achieved with the accumulator. In the field, time-varying pressure measurements were made to characterize the pressure release from full pressure at various release valve positions. Position 1 corresponded to the valve about 1⁄4 open up to Position 7 representing the valve

fully open. Based on this data, the airflow was deduced based on known pressure vs. flow curves for a given orifice size (Figure 24).

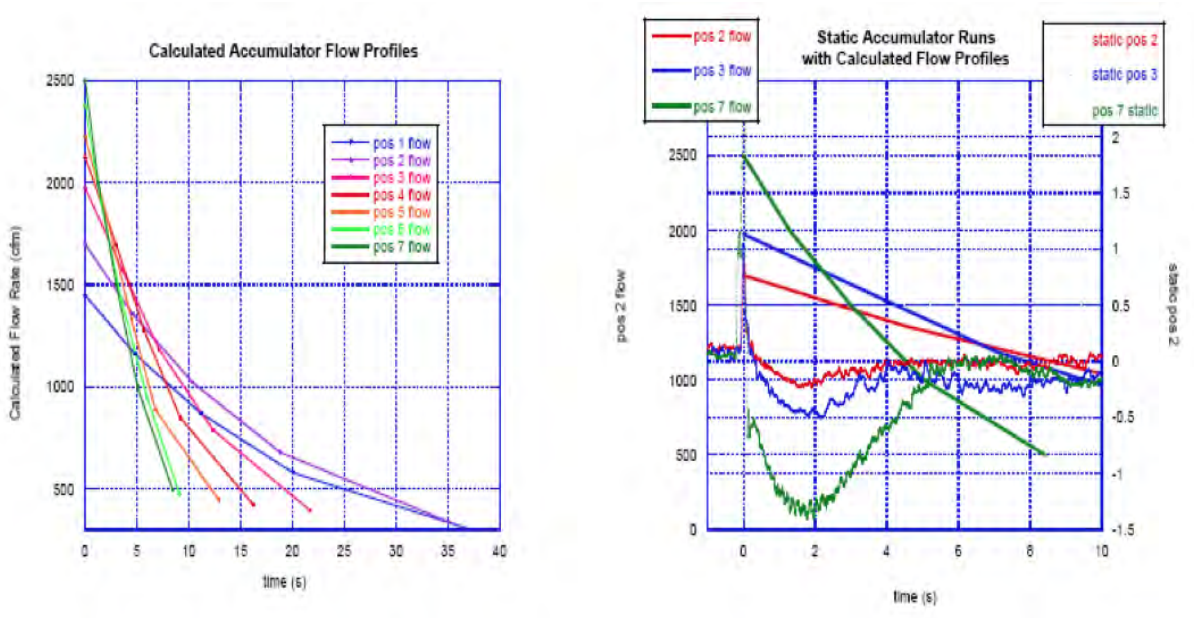

Figure 24. Left: Time-varying airflow calculated for the accumulator system at various valve positions Right: Corresponding calculated pressure curves with stationary Bubble Squid tests for varying accumulator valve positions

The graph on the right of Figure 24 suggests that peak airflow of almost 2500 cfm was achieved, but that flow rate decreased very rapidly and only yielded an average airflow over the Bubble Squid hose area of about 1200 cfm. The stationary bubbler tests on the right graph of Figure 24 suggest that the basic length scales look reasonable, but, as expected, the fluid response to the rapidly varying flow rate was delayed and potentially complex. Based on the comparison of the lower-flow accumulator valve settings with the continuous compressor results for static testing, it seems that the accumulator air flow calculation may overestimate the total flow by up to a factor of 2.

2. Profile Magnitude

The goal of the previous section was to establish a reasonable air flow model to determine the mathematical relationship between the total, continuous

air flow rate and the magnitude of the resulting pressure drop signal. Based on the analysis of data recorded during DTMB testing it seems reasonable to average the airflow rate corresponding to the center 20% of the pressure peak and then use that as a representative air flow rate for establishing the peak height which occurs at time step 2 seen in Figure 21. This was a critical assumption for use in the BSQ model to establish the total airflow required in order to achieve the desired pressure threshold and required pressure signal duration.

Somewhat surprisingly (based on NPS results), the pressure peak height magnitude increases very linearly with increased air flow, even beyond 1500 cfm. This suggests that there was no saturation of total void fraction, which was suspected in earlier static tank testing. This may have been due to the much faster bubble rise times observed at DTMB. The rise times were up to almost 1 m/s, primarily due to the larger mean bubble size achievable. Another possibility for the faster rise times was the greater volume of upwelling water caught in the bubble plume, which would increase the overall velocity profile of the bubbles.

It should be noted that the pressure signals created during data runs using the accumulator do not correspond to the same decay slope observed in the constant-compressor data runs. This may have been due to the impulsive nature of the rapidly decreasing air flow release from the accumulator. Based on the bubble rise velocity for the decay slope variation observed in our constant air flow cases, there was no reason to expect a modified decay slope on the basis of bubble rise time. The accumulator rise time results were not found to be significantly different than those observed during constant air runs. Again, this was accounted for in the BSQ program by establishing a multiplier for the decay slope that can be manually adjusted. Results found during DTMB testing were used to develop a linear relationship to be used in the BSQ program in order to establish the peak pressure drop at time step 2, and the overall shape of the pressure drop.

3. Bubble Squid Hose Length Effects

Two approaches may be used to achieve the desired dwell time below a prescribed pressure threshold. The first approach is to make the overall pressure deviation large enough to remain under the threshold based on the natural peak shape, created from the front and decay slopes. In this case, the pressure signal drops below threshold at time step 1 and returns above threshold at time step 4. The second approach is to add sufficient length to the Bubble Squid hoses to allow a significant dwell time over the pressure sensor. This significant dwell time was found to keep the overall pressure drop observed below the desired pressure threshold. In this case the pressure drops below threshold at time step 1, the Bubble Squid dwells above the pressure sensor until time step 5, and returns above threshold at time step 7.

In order to evaluate the dwell-time behavior of the system for the BSQ model, data corresponding to runs at 1 knot and 3 knots were analyzed for Bubble Squid geometries in which the hose lengths were varied. Because changing hose length was a time-intensive process requiring the entire unit to be removed from the water with an overhead crane, the number of different configurations tested was limited. A system with no hoses, open-air jets, was tested, along with tentacle lengths of 0.3m, 1m, 2m, and 3m. Figure 26 shows results from these systems performed at tow speeds of 1 knot and 3 knots, with the dwell time of the array noted by vertical bars of the same color as the corresponding trace.

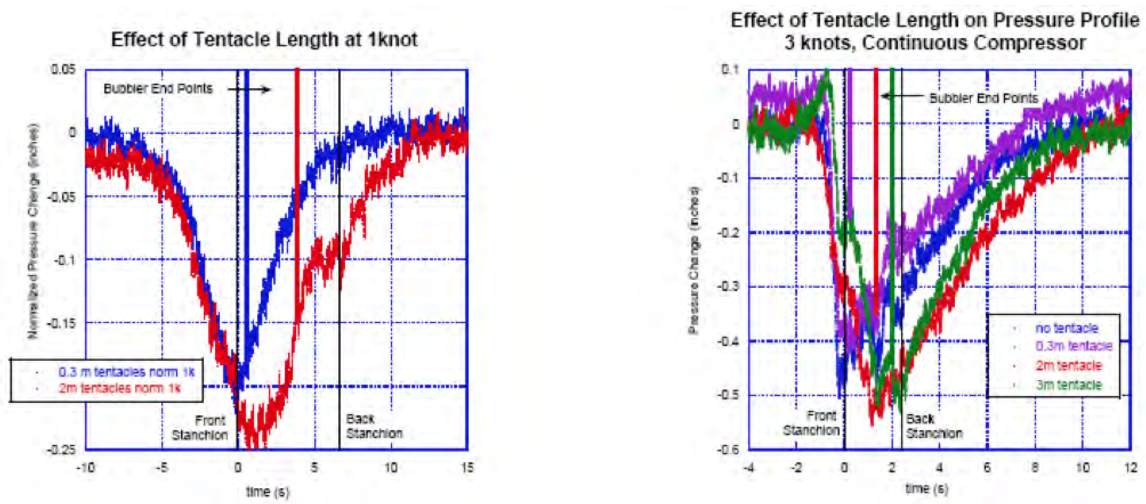

Figure 25. Pressure traces for various bubbler lengths. Left: 1-knot tow velocity Right: 3-knot tow velocity. “no tentacle” corresponds to open-air jets at the Bubble Squid manifold

An interesting element that can be seen in the traces in Figure 25 was the return to the expected decay slope immediately after the passage of the Bubble Squid hose array. In the 1-knot trials, however, significant variation of the pressure during the time in which the Bubble Squid was over the pressure sensor was observed, at least for the 2-meter hose case. In the 3-knot testing on the right, the variation in pressure during the dwell time was often hard to ascertain due to the very short dwell time. However, in general, the pressure seemed to be continuing to drop during the transit of the Bubble Squid array.

Another opportunity for assessing the effect of dwell time was achieved by performing static testing in which the Bubble Squid hose array was stopped just over the top of the pressure sensor bar. In this case the stationary Bubble Squid served as a surrogate for an infinitely long moving bubbler. Such testing appeared to be very sensitive to the basin size and wall effects, as a stationary signal was not detectable during any testing performed at NPS or in testing at TA. However, at DTMB a stationary signal was observed with both the continuous compressor and the accumulator. In both cases, an initial pressure peak was followed by a steady-state pressure drop that persisted with continued

air flow. It was not clear if the initial peak was generated by a hydrodynamic reaction or this was due to an instantaneous high air flow after the release valve was opened on either system. If it was a hydrodynamic response, then the ratio of the peak height to the steady-state value might be a reasonable model of the relative peak height (at time step 2) to dwell-time pressure (between time steps 3 and 5) in a scaled system. Figure 27 illustrates this phenomenon seen during static data runs using continuous air flow.

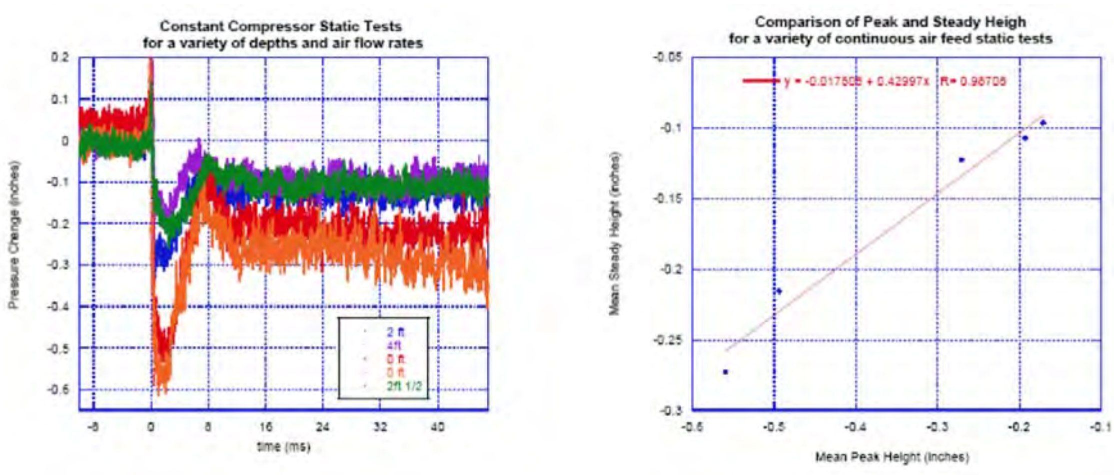

Figure 26. Left: Static bubbler tests at various depths. Right: The relationship between peak pressure and steady-state pressure

The linear least-squares fit shown on the right side of Figure 27 establishes an averaged ratio of the mean steady pressure to the peak pressure height of 0.43. It was unknown whether this was a reasonable assumption for the ratio of peak and dwell pressures for use in a large-scale system. Therefore, in the BSQ model, a user-definable peak to dwell ratio was added. A range between 100%, meaning that the dwell pressure was the same as the peak pressure, and 43%, meaning that the moving pressure signature corresponds to the shape of the static testing found at the DTMB, can be continuously varied and the result of the system performance determined.

4. BSQ Model Results

As described above, the goal of the preceding analysis has been to establish mathematical relations to allow for reasonable predictions of how a full-scale Bubble Squid system would perform. To do this a spreadsheet program was developed based on the information garnered from DTMB data collection. The variables involved in this model are described in Table 3.

Variable	Type	Source
Tow Speed	Input	User Input
Air Flow	Input	Equivalent air flow for the DTMB air compressor unit
Flow per meter of hose	Output	Equivalent flow from above divided by the total Bubble Squid hose length from the DTMB testing Bubble Squid
Total Flow Required	Output	Total flow required based on hose length to achieve same flow per meter of the test Bubble Squid
Threshold	Input	Pressure threshold desired, usually set to 1 inch
Dwell Time	Input	Required time for the pressure to remain under the above threshold value, usually set to desired 10 seconds
Front Slope	Output	Developed from power law
t_1-t_0	Output	Determined from front slope
P_{max}	Output	Determined from linear relationship developed above
t_2-t_0	Output	Determined from front slope and peak height
Peak to steady ratio	Input	User input from 43% to 100%
P_{eq}	Output	Dwell time pressure, determined from the peak pressure and the ratio above
t_3-t_0	Output	Determined from the back slope and the pressure difference from max and eq
t_4-t_0	Output	only for short hose lengths: determined from P_{max} and the back slope
length	Output	Length required is determined from the required dwell time, P_{eq} and t_7-t_5
t_5-t_0	Output	Determined by length and tow speed
Back Slope	Output	Determined by the power law
Back Slope Multiplier	Input	Allows the user to modify the back slope
t_7-t_5	Output	Determined by the back slope
t_7-t_3	Output	determined by the above and length
Final Dwell Time	Output	Can be determined by either peak pressure drop and back slope decay to threshold, or from the length correspondence to the dwell time

Table 3. BSQ model variables and their descriptions

Time step variables used in the BSQ model program are the same as the time steps from Figure 23. Based on these variables, a wide variety of system configurations are possible. Generally, the most important and immediate

question that needed to be answered was how much air flow would be required to achieve the requested ONR system performance of a pressure drop of 1-inch for a dwell time of 10 seconds. This may be evaluated in terms of a range of the unknown quantities, most notably the back slope (the slope between time steps 2 and 3) and the peak-to-equilibrium pressure ratio (the ratio of the pressure values of time steps 2 and 3).

Maintaining the peak-to-equilibrium ratio at 75%, suggested by the moving bubbler tests presented above, a tow speed of 3 knots, a threshold of 1 inch, and minimum dwell time of 10 seconds, the following results are obtained when varying the back slope multiplier as shown in Table 4.

Back Slope (inch/s)	Hose Length (m)	P_{Max} (inches)	P_{eq} (inches)	Dwell Time (s)	Total Flow Required (cfm)
0.041	3	-1.55	-1.16	13.2	2150
0.047	3	-1.55	-1.16	11.8	2150
0.052	3	-1.55	-1.16	10.6	2150
0.078	4	-1.55	-1.16	10	2867
0.100	4.4	-1.55	-1.16	10	3182

Table 4. BSQ modeling with varying back slope

The results here indicate that for a total flow of 2150 cfm, the front and back slope alone are sufficient to create a dwell time below 1 inch for greater than 10 seconds. However, as the back slope is increased, the need arises for increased Bubble Squid hose length in order to maintain an equilibrium pressure below 1 inch, with an increased need for higher air flow.

If we maintain the back slope at 0.041 inch/s with the same other conditions, except vary the equilibrium pressure ratio, the data in Table 5 result:

Back Slope (inch/s)	Hose Length (m)	P_{Max} (inches)	P_{eq} (inches)	Dwell Time (s)	Total Flow Required (cfm)
0.041	-	-1.44	-0.72	< 10	-
0.041	3.5	-1.44	-1.00	10	2150
0.041	4	-1.44	-1.40	10	2666

Table 5. BSQ modeling with varying P_{eq}

In the first case, the peak pressure was not enough to meet the 10 second requirement without an extended array, also the equilibrium pressure was below the one-inch mark, therefore no solution was possible. However, as the equilibrium pressure rises above 1 inch, the effect of a longer hose length can be seen to extend the dwell time. It can also be seen that this also requires a larger amount of total air required.

Finally, holding the peak-to-equilibrium ratio to 75%, the back slope multiplier at 1 and varying the air flow rate gives the results in Table 6.

Back Slope (inch/s)	Hose Length (m)	P_{Max} (inches)	P_{eq} (inches)	Dwell Time (s)	Total Flow Required (cfm)
0.052	-	-1.23	-0.92	< 10	1700
0.052	3.7	-1.34	-1.00	10	2300
0.052	3	-1.45	-1.10	10.5	2050
0.052	3	-1.55	-1.20	10.8	2150

Table 6. BSQ modeling with varying air flow rate

Here we see that as we increase the air flow per foot of bubbler hose, a non-solution condition occurs at 1700 cfm. The peak pressure was not enough

to create a peak wide enough to span the required 10 inches and the equilibrium pressure was too low to make a longer array an alternative.

As the flow rate increases, the equilibrium pressure meets the 1-inch pressure drop requirement and nearly an extra meter of bubbler length creates the required dwell time. However, with a higher air flow rate, the peak height becomes large enough to sustain the 10-second dwell time, reducing the bubbler length back to 3m and reducing the total air required. As air flow continues to increase, both the dwell time and the total flow increase together.

These model outputs reflect the surprising result that with the current model, a larger bubbler array does not benefit the overall design because the added air appears to naturally increase the dwell time through the constant decay slope value. Therefore, a bubbler array of approximately 3 meters length should achieve the required dwell time independent of tow speed. This result was encouraging with regards to payload size, drag, and operational tempo. Additional testing was required to verify the constancy of the decay rate at larger absolute pressure deviations.

5. Summary of DTMB results

This chapter covers the initial data analysis effort of the Phase II Bubble Squid DTMB test series and resulting initial Phase III full-scale modeling. Two key performance parameters, which were impossible to measure at the DTMB, remain as unanswered questions. What is the behavior of the decay slope following large pressure excursions? What is the pressure signal created by long bubbler arrays with significant dwell time at operational tow speeds? Additional testing of a 3m x 3m unit appears to be the best way to fully characterize these values. With the current data and best estimates of these parameters, it appears that a Bubble Squid of the current 1/10 scale with a total air flow of 2050 cfm would create the required 1-inch pressure excursion for ten seconds. This flow rate was not outside the capability of current off-the-shelf compressors, but the feasibility of the system depends on the weight and power requirements of the

compressor. The 11-meter RHIB, which has been the target craft since the Phase I effort was started, has a maximum cargo capacity of 3200 lbs. The 500cfm compressor used at DTMB is rated at 3200 lbs, but this included significant added weight to reduce vibration and noise in industrial settings. Additionally, there were pulsed air release tests used to try and verify what the effects of non-continuous air release scenarios would return. Based on the kinematic response time of the water column, pulsed air release at frequencies above about 5Hz should have similar pressure signatures as continuous air release, but it was unknown without additional testing if this can be converted into a reduction in the total air flow rate required to achieve the desired pressure effect. The use of pulsed release could ease the pressure and continuous flow-rate requirements of the compressor. Other compressor architectures, such as a sealed blower or turbine fan, are still under consideration.

In addition, data regarding the lateral scale of the pressure signature and scaling of the system in the lateral direction were not gathered. Data were taken at DTMB regarding the optimal separation of the bubbler hoses, and this data suggested that additional separation, and therefore additional lateral extent without additional air flow, was possible. It was thought this would cause the pressure drop to be increased by increasing the lateral scale (with air flow held constant). However, these additional ideas were never tested because upon submission of the Phase II final report to ONR our joint project funding was cancelled.

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VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

From the very beginning of the collaboration between NPS and the TA group, the goal was very simple: create a Bubble Squid capable of producing a 1-inch pressure drop with 10-second duration. The process of developing the first Bubble Squid took a long time; there were many materials questions that had to be analyzed. In the end the porous hosing and metal manifold chosen were able to make evaluating the Bubble Squid concept a reality. All of the theory that was verified prior to starting field-testing indicated that a 1-inch pressure drop would be achievable. However it was never guaranteed that the 10-second duration would be produced.

Data that were collected by Lieutenant Jeff Murawski and the TA group, clearly showed great promise to ONR. Our group was awarded a Phase II contract. The research and results were heading in the right direction for successfully developing a pressure minesweeping apparatus. Further testing of a 1/100 scale model testing at the NPS tow tank was required to make sure that the materials that would be needed to construct the 1/10 scale model for DTMB testing would have the same results as the Phase I testing that had already been performed. Testing at the David Taylor facility was very labor intensive and expensive. The budget only had enough funding for one chance in the model basin to make our 1-inch pressure drop and ten-second duration. The final building of the 1/10 scale model at the DTMB was quite literally the biggest project that most of our team had ever experienced. Testing this massive Bubble Squid was both a joy and a curse. A total of 322 data runs were successfully taken over the two-week testing period with a wide range of configurations for hose length, hose separation and air flows. In the end the 1-inch pressure drop was achieved, unfortunately the 10-second duration was never achieved. The data was thoroughly investigated and examined and final report was presented to ONR. Upon submission of the data and final report to the project sponsors there

was lengthy waiting period to see if a Phase III contract was going to be awarded. Unfortunately for our collaboration team, it was determined that due to not meeting the predetermined 10-second duration of a 1-inch pressure drop and the overall size of the air compressor and accumulator tank required just to achieve the 1-inch pressure drop that our Bubble Squid project would not be feasible for use by the Navy onboard an 11 meter RHIB. There is, however, a large amount of data that can be seen in the DTMB analysis that shows that the Bubble Squid technology could be very useful on larger Naval vessels, such as the AVENGER class minesweepers.

NPS has a larger faculty of some very high-ranking retired officers from all different backgrounds of service. Our group continued to use these faculty members to try to acquire additional funding so that the Bubble Squid idea could be moved all the way into a Phase III open-ocean testing environment. Our persistence was met with much optimism, yet no funding could ever be acquired. This is very unfortunate because the threat of pressure mines to US service members is not going away any time soon. The customary trend with mine warfare has shown that funding continues to decrease in this warfare area until an asset is unfortunate enough to suffer damage due to a mine. Our group's hope is that if there ever was an event involving a U.S. Naval asset and a pressure influence mine, our research would be re-evaluated and additional funding would become available to take the Bubble Squid concept into Phase III open-ocean testing. This would be very beneficial considering how much promise can be seen in the data collected at DTMB once the air compressor was used in conjunction with the accumulator tank. With additional funding and testing at the DTMB the BSQ modeling program clearly suggests that achieving the 1-inch pressure drop with a sustained 10 second duration is very attainable.

The goal of this thesis was to show how a reasonable Bubble Squid apparatus could be designed, built, and tested in order to solve the pressure mine sweeping capability gap. A lot of details went into the selection of materials

and equipment that would be used for performing all of the data collection. The collaboration team from NPA and Templeman Automation worked a great deal of hours in order to solve the pressure minesweeping capability gap.

B. FUTURE WORK

The current Chief of Naval Operations has clearly defined the direction the U.S. Navy is taking using unmanned vehicles. The Navy is going to continue to research and develop the technologies required to make unmanned vehicles take service members out of harm's way when possible. Keeping this trend in mind, the use of the Bubble Squid could be used someday by an unmanned surface vehicle (USV) for minesweeping. Figure 28 shows the Brooke-Ocean Company's rendition of where they believe USVs are heading.

Figure 27. The future for USV technology (From ODIM Brooke Ocean, April 22, 2010)

With so much effort being placed on the production and improvements of USVs for Naval application, it seems only a matter of time before there will be a vehicle capable of maintaining operation with the equipment needed to make the

Bubble Squid concept possible. Funding could also be applied to the manufacturing of a small lightweight air compressor that would be capable of producing the required air flow need to generate the 1-inch pressure drop with 10-second duration. Either way, this thesis proves that the theory and direction of the TA group and NPS were clearly heading in the right direction towards solving the capability gap of effectively being able to minesweep for pressure-actuated mines.

APPENDIX A NPS TOW TANK DATA RUN TABLE

Run #	Date	Tow Velocity (m/s)	Sensor to BS Sep (in)	Air Supply	Bubble Squid Depth
Start Runs 4 hoses 25cm long, 12.5 cm apart					
1	8Mar	0.25	6	none	36 inches
2	8Mar	0.25	6	none	36
3	8Mar	1	6	none	36
4	8Mar	1	6	none	36
5	8Mar	1	6	none	36
6	8Mar	1	6	none	36
7	8Mar	1	6	~ half	36
8	8Mar	1	6	full	36
9	8Mar	0.25	6	full	36
10	8Mar	0.25	6	full	36
11	8Mar	0.75	6	none	36
12	8Mar	0.75	6	none	36
13	8Mar	0.75	6	full	36
14	8Mar	0.75	6	full	36
15	8Mar	0.5	6	none	36
16	8Mar	0.5	6	none	36
17	8Mar	0.5	6	full	36
18	8Mar	0.5	6	full	36
19	8Mar	0.63	6	none	36
20	8Mar	0.63	6	none	36
21	8Mar	0.63	6	full	36
22	8Mar	0.63	6	full	36
Starting Data runs with same configuration as previous day					
23	9Mar	0.3	6	none	36
24	9Mar	0.3	6	none	36
25	9Mar	0.3	6	full	36
26	9Mar	0.3	6	full	36
27	9Mar	0.4	6	none	36
28	9Mar	0.4	6	none	36
29	9Mar	0.4	6	full	36
30	9Mar	0.4	6	full	36
31	9Mar	0.56	6	none	36
32	9Mar	0.56	6	none	36
33	9Mar	0.56	6	none	36
34	9Mar	0.56	6	full	36
35	9Mar	0.56	6	full	36
36	9Mar	0.68	6	none	36
37	9Mar	0.68	6	none	36

Run #	Date	Tow Velocity (m/s)	Sensor to BS Sep (in)	Air Supply	Bubble Squid Depth
38	9Mar	0.68	6	full	36
39	9Mar	0.68	6	full	36
40	9Mar	0.83	6	none	36
41	9Mar	0.83	6	none	36
42	9Mar	0.83	6	full	36
43	9Mar	0.83	6	full	36
44	9Mar	0.92	6	none	36
45	9Mar	0.92	6	none	36
46	9Mar	0.92	6	full	36
47	9Mar	0.92	6	full	36
Pressure sensor taken off stand and placed on bottom of tow tank, clearance from sensor now about 14 inches, Bubble Squid lowered on stanchion					
48	9Mar	0.25	14	none	61
49	9Mar	0.25	14	none	61
50	9Mar	0.25	14	none	61
51	9Mar	0.25	14	full	61
52	9Mar	0.25	14	full	61
53	9Mar	0.75	14	full	61
54	9Mar	0.75	14	full	61
55	9Mar	0.75	14	full	61
56	9Mar	0.75	14	none	61
Bubble Squid lowered by stanchion for 4 inch clearance from Sensor					
57	9Mar	0.75	4	none	71
58	9Mar	0.75	4	full	71
59	9Mar	0.5	4	none	71
60	9Mar	0.5	4	full	71
61	9Mar	0.3	4	none	71
62	9Mar	0.3	4	full	71
63	9Mar	0.3	4	~half	71
64	9Mar	0.1	4	~half	71
65	9Mar	0.1	4	~half	71
Starting data runs with same setting as ending from previous day					
66	10Mar	0.5	4	none	71
67	10Mar	0.5	4	full	71
68	10Mar	0.1	4	none	71
69	10Mar	0.1	4	none	71
70	10Mar	0.1	4	full	71
71	10Mar	0.1	4	full	71
72	10Mar	0.1	4	none	71
73	10Mar	0.5	4	none	71
74	10Mar	0.5	4	none	71

Run #	Date	Tow Velocity (m/s)	Sensor to BS Sep (in)	Air Supply	Bubble Squid Depth
75	10Mar	0.5	4	full	71
Needing to be able to vary height from sensor bar greater than able to with yellow stanchion, fabricated an extension bar to add to the tow carriage stanchion. A-H refer to hole on yellow stanchion then with or without extension for height above pressure sensor					
76	10Mar	0.5	5	full	E + extension
77	10Mar	1	5	none	E + extension
78	10Mar	1	5	none	E + extension
79	10Mar	1	5	full	E + extension
80	10Mar	1	5	full	E + extension
81	10Mar	0.5	5	none	E + extension
82	10Mar	0.5	5	none	E + extension
83	10Mar	0.5	5	full	E + extension
84	10Mar	0.5	5	full	E + extension
85	10Mar	1	10	none	D + extension
86	10Mar	1	10	none	D + extension
87	10Mar	1	10	full	D + extension
88	10Mar	1	10	full	D + extension
89	10Mar	0.5	10	none	D + extension
90	10Mar	0.5	10	none	D + extension
91	10Mar	0.5	10	full	D + extension
92	10Mar	0.5	10	full	D + extension
93	10Mar	1	15	none	C + extension
94	10Mar	1	15	none	C + extension
95	10Mar	1	15	full	C + extension
96	10Mar	1	15	full	C + extension
97	10Mar	0.5	15	none	C + extension
98	10Mar	0.5	15	none	C + extension
99	10Mar	0.5	15	full	C + extension
100	10Mar	0.5	15	full	C + extension
101	10Mar	1	20	none	B + extension
102	10Mar	1	20	none	B + extension
103	10Mar	1	20	full	B + extension
104	10Mar	1	20	full	B + extension
105	10Mar	0.5	20	none	B + extension
106	10Mar	0.5	20	none	B + extension
107	10Mar	0.5	20	full	B + extension
108	10Mar	0.5	20	full	B + extension
109	10Mar	1	25	none	A + extension
110	10Mar	1	25	none	A + extension
111	10Mar	1	25	full	A + extension
112	10Mar	1	25	full	A + extension
Extension bar removed, Height now just based on holes from stanchion bar					
113	10Mar	0.5	39	none	H

Run #	Date	Tow Velocity (m/s)	Sensor to BS Sep (in)	Air Supply	Bubble Squid Depth
114	10Mar	0.5	39	none	H
115	10Mar	0.5	39	full	H
116	10Mar	0.5	39	full	H
117	10Mar	1	39	none	H
118	10Mar	1	39	none	H
119	10Mar	1	39	full	H
120	10Mar	1	39	full	H
121	10Mar	0.5	44	none	G
122	10Mar	0.5	44	none	G
123	10Mar	0.5	44	full	G
124	10Mar	0.5	44	full	G
125	10Mar	1	44	none	G
126	10Mar	1	44	none	G
127	10Mar	1	44	full	G
128	10Mar	1	44	full	G
129	10Mar	0.5	49	none	F
130	10Mar	0.5	49	none	F
131	10Mar	0.5	49	full	F
132	10Mar	0.5	49	full	F
133	10Mar	1	49	none	F
134	10Mar	1	49	none	F
135	10Mar	1	49	full	F
136	10Mar	1	49	full	F
137	10Mar	1	49	full	F
138	10Mar	1	54	none	E
139	10Mar	1	54	none	E
140	10Mar	1	54	full	E
141	10Mar	1	54	full	E
142	10Mar	1	59	full	D
143	10Mar	1	59	full	D
After analyzing data from previous days testing NPS and TA both agreed that bow shock from the Bubble Squid manifold is affecting pressure drop, non-porous tubing added to each of the four hoses to provide 91 cm bubble free zone behind manifold.					
144	11Mar	0.5	39	none	H
145	11Mar	0.5	39	full	H
146	11Mar	1	39	none	H
147	11Mar	1	39	full	H
148	11Mar	1	39	full	H
Extension Bar re-attached to stanchion					
149	11Mar	0.5	10	none	D + extension
150	11Mar	0.5	10	full	D + extension

Run #	Date	Tow Velocity (m/s)	Sensor to BS Sep (in)	Air Supply	Bubble Squid Depth
151	11Mar	0.75	10	none	D + extension
152	11Mar	0.75	10	full	D + extension
High accuracy flowmeter installed to verify airflow through Bubble Squid as it travels over the pressure sensor.					
153	11Mar	0.33	5	none	E + extension
154	11Mar	0.33	5	full	E + extension
155	11Mar	0.33	5	~ half	E + extension
156	11Mar	0.33	5	~ half	E + extension
157	11Mar	0.33	5	~ quarter	E + extension
158	11Mar	0.33	5	~ quarter	E + extension
159	11Mar	0.33	5	250 l/m	E + extension
160	11Mar	0.33	5	250 l/m	E + extension
161	11Mar	0.33	5	218 l/m	E + extension
162	11Mar	0.33	5	225 l/m	E + extension
163	11Mar	0.33	5	135 l/m	E + extension
164	11Mar	0.33	5	135 l/m	E + extension
165	11Mar	0.33	5	100 l/m	E + extension
166	11Mar	0.33	5	100 l/m	E + extension
167	11Mar	0.33	5	75 l/m	E + extension
168	11Mar	0.33	5	75 l/m	E + extension
169	11Mar	0.33	5	50 l/m	E + extension
170	11Mar	0.33	5	50 l/m	E + extension
171	11Mar	0.33	5	<Missed>	E + extension
172	11Mar	0.33	5	<Missed>	E + extension
Long Non-porous hoses replaced with porous hoses, hoses now 4 at 119 cm					
173	11Mar	0.33	5	full	E + extension
174	11Mar	0.33	5	full	E + extension
175	11Mar	0.33	5	full	E + extension
176	11Mar	0.33	5	140 l/m	E + extension
177	11Mar	0.33	5	270 l/m	E + extension
178	11Mar	0.33	5	270 l/m	E + extension
179	11Mar	0.33	5	270 l/m	E + extension
180	11Mar	0.33	5	270 l/m	E + extension
181	11Mar	0.5	5	270 l/m	E + extension
182	11Mar	0.5	5	270 l/m	E + extension
183	11Mar	0.33	5	none	E + extension
184	11Mar	0.5	5	none	E + extension
Same setup as the ending of the previous day					
185	12Mar	0.5	5	256 l/m	E + extension
186	12Mar	0.5	5	256 l/m	E + extension
187	12Mar	0.5	5	256 l/m	E + extension

Run #	Date	Tow Velocity (m/s)	Sensor to BS Sep (in)	Air Supply	Bubble Squid Depth
188	12Mar	0.5	5	256 l/m	E + extension
189	12Mar	0.5	5	none	E + extension
190	12Mar	0.5	5	none	E + extension
191	12Mar	1	5	220 l/m	E + extension
192	12Mar	1	5	245 l/m	E + extension
193	12Mar	1	5	none	E + extension
194	12Mar	1	5	none	E + extension

APPENDIX B DTMB DATA RUN TABLE

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
Tow Carriage A-Frame at its 0 position, Sensor Bar not on stand, Bubble Squid passing 3 feet above sensor bar, all hoses are 2 meters long on the Bubble Squid				
1	17May	Verifying position of Sensor Bar		
2	17May	Moving Tow Carriage over the sensor bar slowly		
3	17May	Stationary above sensor bar, No Bubbles		
4	17May	Stationary, Full Bubbles		
5	17May	1 Knot, No Bubbles		
6	17May	1 Knot With Full bubbles		
7	17May	Stationary above sensor bar to verify no sensor bar movement		
8	17May	Repeat of run #7, Sensor bar appears to have toppled over		
Sensor bar reinforced with weights on the ropes to prevent carriage from attaching during each data run				
9	18May	1 Knot, no Bubbles, Sensor bar appears to be holding		
10	18May	1 Knot, with 100% Bubbles (full Air Compressor flow)		10
11	18May	2 Knots, no Bubbles		
12	18May	2 Knots, 100% Bubbles		50
13	18May	4 Knots, no Bubbles		
14	18May	4 Knots, 100% Bubbles		60
15	18May	6 Knots, no Bubbles		
16	18May	6 Knots, 100% Bubbles		120
17	18May	3 Knots, no Bubbles		
18	18May	3 Knots, 100% Bubbles		
19	18May	5 Knots, no Bubbles		
20	18May	5 Knots, 100% Bubbles		100
21	18May	1 Knot, 100% Bubbles	7.17	
22	18May	1.5 Knots, no Bubbles		
23	18May	1.5 Knots, 100% Bubbles	7.98	
24	18May	2.5 Knots, no Bubbles		
25	18May	2.5 Knots, 100% Bubbles	8.65	
26	18May	3.5 Knots, no Bubbles		
27	18May	3.5 Knots, 100% Bubbles	11.05	
28	18May	4.5 Knots, no Bubbles		
29	18May	4.5 Knots, 100% Bubbles		
30	18May	5.5 Knots, no Bubbles		
31	18May	5.5 Knots, 100% Bubbles	13.18	
32	18May	6.5 Knots, no Bubbles		
33	18May	6.5 Knots, 100% Bubbles	14.11	

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
34	18May	7.5 Knots, no Bubbles		
35	18May	7.5 Knots, 100% Bubbles	13.77	
36	18May	8.5 Knots, no Bubbles		
37	18May	8.5 Knots, 100% Bubbles	15.06	
38	18May	6 Knots, no Bubbles		
39	18May	6 Knots, 100% Bubbles	12.37	
40	18May	6 Knots, no Bubbles		
41	18May	6 Knots, 100% Bubbles	12.72	
42	18May	5 Knots, 100% Bubbles	8.91	
43	18May	2 Knots in Reverse, 100% Bubbles		
44	18May	8.5 Knots, no Bubbles		
45	18May	8.5 Knots, 100% Bubbles	12.58	
A-Frame raised up 4 Feet, Bubble Squid now passing 7 feet above sensor bar				
46	18May	1 Knot, no Bubbles		
47	18May	1 Knot, 100% Bubbles	5.6	
48	18May	2 Knots, no Bubbles		
49	18May	2 Knots, 100% Bubbles		
50	18May	3 Knots, no Bubbles		
51	18May	3 Knots, 100% Bubbles	8.32	
52	18May	6 Knots, no Bubbles		
53	18May	6 Knots, 100% Bubbles	10.26	
A-Frame raised another 4 feet, Bubble Squid now passing 11 feet above sensor bar				
54	18May	1 Knot, no Bubbles		
55	18May	1 Knot, 100% Bubbles	2.71	
56	18May	2 Knots, no Bubbles		
57	18May	2 Knots, 100% Bubbles	4.32	
58	18May	3 Knots, no Bubbles		
59	18May	3 Knots, 100% Bubbles	5.05	
60	18May	6 Knots, no Bubbles		
61	18May	6 Knots, 100% Bubbles	6.24	
A-Frame at 0 position, Air dump valve and Y valve installed on Air Compressor to check for air flow performance vs. the observed pressure drop, bleed valve openings are crude estimates				
62	19May	3 Knots, no Bubbles		
63	19May	3 Knots, 100% Bubbles	8.65	
64	19May	3 Knots, Air Compressor Bleed Valve 1/4 open (22.5 degrees)	7.65	
65	19May	3 Knots, Air Compressor Bleed Valve 1/2 open (45 degrees)	10.38	

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
66	19May	3 Knots, Air Compressor Bleed Valve 1/8 open (12.25 degrees)	7.44	
Sensor Bar placed on a stand, Raises Sensor bar to 1/2 inch of clearance when A-Frame at 0 position, A-Frame raised 11.5 inches to give a 1 Foot clearance of the Bubble Squid above the sensor bar				
67	19May	1 Knot, no Bubbles		
68	19May	1 Knot, 100% Bubbles		
69	19May	2 Knots, no Bubbles		
70	19May	<<Not Logged>>		
71	19May	2 Knots, 100% Bubbles		
72	19May	3 Knots, no Bubbles		
73	19May	3 Knots, 100% Bubbles		
74	19May	<<Not Logged>>		
75	19May			
76	19May			
77	19May			
Bubble Squid craned out of water and 3 meter hoses replaced with 1 meter hoses, performed optest of 1 meter hoses with 100% Bubbles - OPTEST SAT				
78	19May	1 Knot, no Bubbles		
79	19May	1 Knot, 100% Bubbles		
80	19May	2 Knots, no Bubbles		
81	19May	2 Knots, 100% Bubbles		
82	19May	3 Knots, no Bubbles		
83	19May	1 Knot, no Bubbles		
84	19May	1 Knot, 100% Bubbles		
85	19May	2 Knots, no Bubbles		
86	19May	3 Knots, Air Compressor Bleed Valve 1/8 open (12.25 degrees)		
87	19May	3 Knots, Air Compressor Bleed Valve 1/4 open (22.5 degrees)		
88	19May	3 Knots, Air Compressor Bleed Valve 1/2 open (45 degrees)		
A-Frame Raised another 12 inches, now at 23.5 inches for a 2 foot clearance of Bubble Squid above sensor bar				
89	19May	3 Knots, 100% Bubbles		
Bubble Squid craned out of water and 1 meter hoses replaced with ten 2 meter hoses, five on each side of center, other nozzles are now plugged, performed optest of 2 meter hoses with 100% Bubbles - OPTEST SAT				
90	20May	Stationary test, Bubble Squid positioned over top of sensor bar, 100% Bubbles		
91	20May	Stationary test, Air Compressor Bleed Valve 1/8 open		
92	20May	Stationary test, Air Compressor Bleed Valve 1/4 open		

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
A-Frame lowered 1 foot for a clearance of 1 Foot from Bubble Squid to sensor bar				
93	20May	Stationary test, 100% Bubbles		
94	20May	1 Knot, no Bubbles		
95	20May	1 Knot, 100% Bubbles		
96	20May	2 Knots, no Bubbles		
97	20May	2 Knots, 100% Bubbles		
98	20May	3 Knots, 100% Bubbles		
99	20May	6 Knots, 100% Bubbles		
100	20May	8 Knots, 100% Bubbles		
All Hoses nozzles refitted with 3 meter long hoses, A-Frame still up 11.5 inches for 1 foot clearance above sensor bar				
101	20May	Stationary test, 100% Bubbles		
102	20May	Stationary test, Air Compressor Bleed Valve 1/8 open		
103	20May	Stationary test, Air Compressor Bleed Valve 1/4 open		
104	20May	1 Knot, no Bubbles		
105	20May	1 Knot, 100% Bubbles		
106	20May	2 Knots, 100% Bubbles		
107	20May	3 Knots, 100% Bubbles		
108	20May	6 Knots, 100% Bubbles		
109	20May	6 Knots, no Bubbles		
110	20May	3 Knots, Air Compressor Bleed Valve 1/8 open (12.25 degrees)		
A-Frame raised 3 feet for a total 4 foot clearance above the sensor bar				
111	20May	1 Knot, 100% Bubbles		
112	20May	2 Knots, 100% Bubbles		
113	20May	3 Knots, 100% Bubbles		
114	20May	6 Knots, 100% Bubbles		
115	20May	6 Knots, no Bubbles		
116	20May	8 Knots, no Bubbles		
117	20May	8 Knots, 100% Bubbles		
118	20May	Observing how tank standing waves affecting Pressure sensors		
119	20May	8 Knots, no Bubbles		
120	20May	8 Knots, 100% Bubbles		
A-Frame raised 4 feet, total 8 feet clearance above the sensor bar				
121	20May	3 Knots, 100% Bubbles		
122	20May	6 Knots, 100% Bubbles		
123	20May	Standing waves in Tow Tank observed		
Performing static runs above the sensor bar while varying air flow and height while recording data, also a pulsating effect of the Air Compressor				
124	20May	Bubble Squid moved vertically, 100% Bubbles after 30 sec		
125	20May	100% Bubbles at 17 sec, Bubble Squid moved up at 45 sec		
126	20May	100% Bubbles at 15 sec, Bubble Squid moved down at 40 sec		
127	20May	A frame at 11.5 inches, Bubbles pulsed off and on		

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
128	20May	Repeat of Bubbles pulsed off and on		
129	20May	A-Frame at 4 feet of clearance above sensor bar		
130	20May	A-Frame at 2 feet of clearance above sensor bar		
131	20May	Intermittent use of Air Compressor		
132	20May	Intermittent use of Air Compressor		
A-Frame placed at 23.5 inches for 2 foot clearance above the sensor bar				
133	21May	Check of the steady state of the tank prior to runs		
134	21May	8 Knots, 100% Bubbles		
135	21May	Standing wave observations after high speed run		
136	21May	Standing wave observations after high speed run		
137	21May	Standing wave observations after high speed run		
138	21May	Standing wave observations after high speed run		
139	21May	Stationary above sensor bar, 100% Bubbles		
140	21May	Stationary, Air Compressor Bleed Valve 1/2 open		
141	21May	1/2 Knot, no Bubbles		
142	21May	1/2 Knot, Air Compressor Bleed Valve 1/2 open		
143	21May	1/2 Knot, 100% Bubbles		
144	21May	1 Knot, no Bubbles		
145	21May	1 Knot, Air Compressor Bleed Valve 1/2 open		
146	21May	1 Knot, 100% Bubbles		
147	21May	1.5 Knots, no Bubbles		
148	21May	1.5 Knots, Air Compressor Bleed Valve 1/2 open		
149	21May	1.5 Knots, 100% Bubbles		
150	21May	2 Knots, no Bubbles		
151	21May	2 Knots, Air Compressor Bleed Valve 1/2 open		
152	21May	2 Knots, 100% Bubbles		
153	21May	2.5 Knots, no Bubbles		
154	21May	2.5 Knots, Air Compressor Bleed Valve 1/2 open		
155	21May	2.5 Knots, 100% Bubbles		
156	21May	3 Knots, no Bubbles		
157	21May	3 Knots, Air Compressor Bleed Valve 1/2 open		
158	21May	3 Knots, 100% Bubbles		
159	21May	3.5 Knots, no Bubbles		
160	21May	3.5 Knots, Air Compressor Bleed Valve 1/2 open		
161	21May	3.5 Knots, 100% Bubbles		
162	21May	Standing wave observations		
163	21May	3.5 Knots, 100% Bubbles		
164	21May	4 Knots, no Bubbles		
165	21May	4 Knots, Air Compressor Bleed Valve 1/2 open		
166	21May	4 Knots, 100% Bubbles		
A-Frame placed at 35.5 inches for 3 foot clearance above the sensor bar				
167	21May	Stationary above sensor bar, no Bubbles		

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
168	21May	Stationary, Air Compressor Bleed Valve 1/2 open		
169	21May	Stationary, 100% Bubbles		
170	21May	1/2 Knot, no Bubbles		
171	21May	1/2 Knot, Air Compressor Bleed Valve 1/2 open		
172	21May	1/2 Knot, 100% Bubbles		
173	21May	1 Knot, no Bubbles		
174	21May	1 Knot, Air Compressor Bleed Valve 1/2 open		
175	21May	1 Knot, 100% Bubbles		
176	21May	1.5 Knots, no Bubbles		
177	21May	1.5 Knots, Air Compressor Bleed Valve 1/2 open		
178	21May	1.5 Knots, 100% Bubbles		
A-Frame at 35.5 inches for 3 foot clearance above the sensor bar				
179	24May	Stationary above sensor bar to start day		
180	24May	2 Knots, no Bubbles		
181	24May	2 Knots, Air Compressor Bleed Valve 1/2 open		
182	24May	2 Knots, 100% Bubbles		
183	24May	2.5 Knots, no Bubbles		
184	24May	2.5 Knots, Air Compressor Bleed Valve 1/2 open		
185	24May	2.5 Knots, 100% Bubbles		
186	24May	3 Knots, no Bubbles		
187	24May	3 Knots, Air Compressor Bleed Valve 1/2 open		
188	24May	3 Knots, 100% Bubbles		
189	24May	3.5 Knots, no Bubbles		
190	24May	3.5 Knots, Air Compressor Bleed Valve 1/2 open		
191	24May	3.5 Knots, 100% Bubbles		
192	24May	4 Knots, no Bubbles		
193	24May	4 Knots, Air Compressor Bleed Valve 1/2 open		
194	24May	4 Knots, 100% Bubbles		
A-Frame raised to 59.5 inches for 5 foot clearance above the sensor bar				
195	24May	1/2 Knot, no Bubbles		
196	24May	1/2 Knot, 100% Bubbles		
197	24May	1 Knot, no Bubbles		
198	24May	1 Knot, 100% Bubbles		
199	24May	1.5 Knots, no Bubbles		
200	24May	1.5 Knots, 100% Bubbles		
201	24May	<< Bad Run>>		
202	24May	2 Knots, no Bubbles		
203	24May	2 Knots, 100% Bubbles		
204	24May	2.5 Knots, no Bubbles		
205	24May	2.5 Knots, 100% Bubbles		
206	24May	3 Knots, no Bubbles		
207	24May	3 Knots, 100% Bubbles		

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
208	24May	3.5 Knots, no Bubbles		
209	24May	3.5 Knots, 100% Bubbles		
210	24May	4 Knots, no Bubbles		
211	24May	4 Knots, 100% Bubbles		
Static runs, hose configuration changed to alternating hose/no hose configuration, varying height configurations				
212	24May	1 foot clearance, Air Compressor Bleed Valve 1/2 open		
213	24May	1 foot clearance, 100% Bubbles		
214	24May	2 foot clearance, Air Compressor Bleed Valve 1/2 open		
215	24May	2 foot clearance, 100% Bubbles		
216	24May	3 foot clearance, 100% Bubbles		
217	24May	4 foot clearance, 100% Bubbles		
218	24May	5 foot clearance, 100% Bubbles		
Regular data runs, A-Frame at 11.5 inches for 1 foot clearance above sensor bar				
219	24May	3 Knots, no Bubbles		
220	24May	3 Knots, Air Compressor Bleed Valve 1/2 open		
221	24May	3 Knots, 100% Bubbles		
Model Change: switched to air jets, A-Frame at 1 foot clearance				
222	24May	Static run above sensor bar, Bleed Valve 1/2 open		
223	24May	Static run above sensor bar, 100% Bubbles		
224	24May	Extra slow run over sensor bar, 100% Bubbles		
225	24May	3 Knots, 100% Bubbles		
A-Frame placed at 11.5 inches for 1 foot clearance above sensor bar, all hoses attached with 3 meter hoses				
226	25May	1/2 Knots, no Bubbles		
A-Frame still at 1 foot clearance, Air Accumulator tank added onto the Tow Carriage				
227	25May	Static test, full accumulator tank burst (81 psi)		
228	25May	Repeat run (79 psi)		
229	25May	Repeat run (81 psi)		
230	25May	Repeat run (100 psi)		
231	25May	Repeat run (100 psi)		
232	25May	Repeat run (75 psi)		
233	25May	Repeat run (75 psi)		
234	25May	Repeat run (92 psi)		
235	25May	Repeat run (94 psi)		
236	25May	92 psi accumulator run with no air compressor, decay curve		
A-Frame raised to 2 foot clearance above sensor bar, continued static runs				
237	25May	Static run (73 psi)		
238	25May	Repeat run (74 psi)		
239	25May	Repeat run (84 psi)		
240	25May	Repeat run (85 psi)		
241	25May	Repeat run (95 psi)		

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
242	25May	Repeat run (93 psi)		
243	25May	Repeat run (106 psi)		
244	25May	Repeat run (106 psi)		
A-Frame raised to 3 foot clearance above sensor bar, continued static runs				
245	25May	Repeat run (75 psi)		
246	25May	Repeat run (85 psi)		
247	25May	Repeat run (95 psi)		
248	25May	Repeat run (105 psi)		
A-Frame raised to 4 foot clearance above sensor bar, continued static runs				
249	25May	Repeat run (74 psi)		
250	25May	Repeat run (85 psi)		
251	25May	Repeat run (93 psi)		
252	25May	Repeat run (105 psi)		
A-Frame raised to 5 foot clearance above sensor bar, continued static runs				
253	25May	Repeat run (73 psi)		
A-Frame lowered to 1 foot clearance, beginning runs at speed with accumulator tank bursts				
254	25May	1 Knot, 102 psi burst over sensor bar		
255	25May	Repeat run		
256	25May	2 Knots		
257	25May	2 Knots		
258	25May	3 Knots		
259	25May	3 Knots		
260	25May	4 Knots		
261	25May	4 Knots		
262	25May	1 Knot, gradual accumulator release (about -.5 psi per second)		
263	25May	1 Knot, gradual accumulator release (about -1 psi per second)		
264	25May	Repeat run		
265	25May	Repeat run		
266	25May	Repeat run		
267	25May	2 Knots, gradual accumulator release		
268	25May	2 Knots, no Bubbles		
269	25May	2 Knots, no accumulator, just Air Compressor Bubbles		
270	25May	2 Knots, gradual accumulator release		
271	25May	Repeat run		
272	25May	Repeat run		
273	25May	Static system check run		
274	25May	Static run with accumulator burst at tank valve position 1		
275	25May	Long drawn out run to measure tow tank noise		
276	25May	2 Knots, gradual accumulator release		
277	25May	Static run, with accumulator tank at valve position 2		
278	25May	Static run, with accumulator tank at valve position 3		
A-Frame placed at 11.5 inches up for 1 foot clearance above sensor bar				

Run #	Date	Comment(s):	Rise Time (sec)	Rise Distance (ft)
279	26May	1 Knot, no Bubbles		
280	26May	1 Knot, 100% Bubbles, no accumulator tank		
281	26May	1 Knot, accumulator tank at valve full open		
282	26May	1 Knot, with accumulator tank at valve position 6		
283	26May	1 Knot, with accumulator tank at valve position 5		
284	26May	1 Knot, with accumulator tank at valve position 4		
285	26May	1 Knot, with accumulator tank at valve position 3	4.21	
286	26May	1 Knot, with accumulator tank at valve position 2		
287	26May	1 Knot, with accumulator tank at valve position 1	5.63	
288	26May	2 Knots, no Bubbles		
289	26May	2 Knots, 100% Bubbles		
290	26May	2 Knots, accumulator tank valve full open	2.96	
291	26May	2 Knots, with accumulator tank at valve position 6	3.8	
292	26May	2 Knots, with accumulator tank at valve position 4	4.6	
293	26May	2 Knots, with accumulator tank at valve position 2	6.1	
294	26May	2 Knots, with accumulator tank at valve position 1	6.05	
295	26May	2 Knots, with accumulator tank at valve position 6	6.46	
296	26May	3 Knots, no Bubbles		
297	26May	3 Knots, 100% Bubbles	11.76	
298	26May	3 Knots, accumulator tank valve full open	4.47	
299	26May	3 Knots, with accumulator tank at valve position 6	4.82	
300	26May	3 Knots, with accumulator tank at valve position 4	6.42	
301	26May	3 Knots, with accumulator tank at valve position 2		
302	26May	3 Knots, with accumulator tank at valve position 1, no Bubs	11.5	
303	26May	Repeat 3 Knots, accumulator tank at valve position 1	9.01	
304	26May	4 Knots, no Bubbles		
305	26May	4 Knots, 100% Bubbles	11.47	
306	26May	4 Knots, accumulator tank valve full open	5.3	
307	26May	4 Knots, with accumulator tank at valve position 6		
308	26May	4 Knots, with accumulator tank at valve position 4	6.73	
309	26May	4 Knots, with accumulator tank at valve position 2	9.05	
310	26May	4 Knots, with accumulator tank at valve position 1	8.98	
311	26May	6 Knots, no Bubbles		
312	26May	Settling run		
313	26May	6 Knots, 100% Bubbles		
314	26May	Settling run		
315	26May	Settling run		
316	26May	Settling run		
317	26May	6 Knots, 100% Bubbles		
318	26May	Settling run		
319	26May	Settling run		
320	26May	Settling run		
321	26May	6 Knots, 100% Bubbles		
322	26May	10 Knots, no Bubbles		

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